Infrared Spectroscopy of Novae
(and other astronomical objects)

by

Catherine C. Venturini, David K. Lynch, Richard J. Rudy, Ray W. Russell,
Stephan M. Mazuk, William Dimpfl, Eric Campbell

The Aerospace Corporation
El Segundo, CA

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THE AEROSPACE CORPORATION

Collaborators

R. C. Puetter
UC San Diego

L. S. Bernstein
Spectral Sciences, Inc.

M. Sitko
Univ. of Cincinnati

R. B. Perry
NASA Langley

A. Witt
Univ. of Toledo

J. Wilson
Univ. of Virginia

P. Hoeflich
Univ. of Texas at Austin

G. Clayton
Louisiana State Univ.

K. Gordon
A. Sprague
Univ. of Arizona at Tucson

C. Grady
NOAO

D. Wooden
NASA Ames

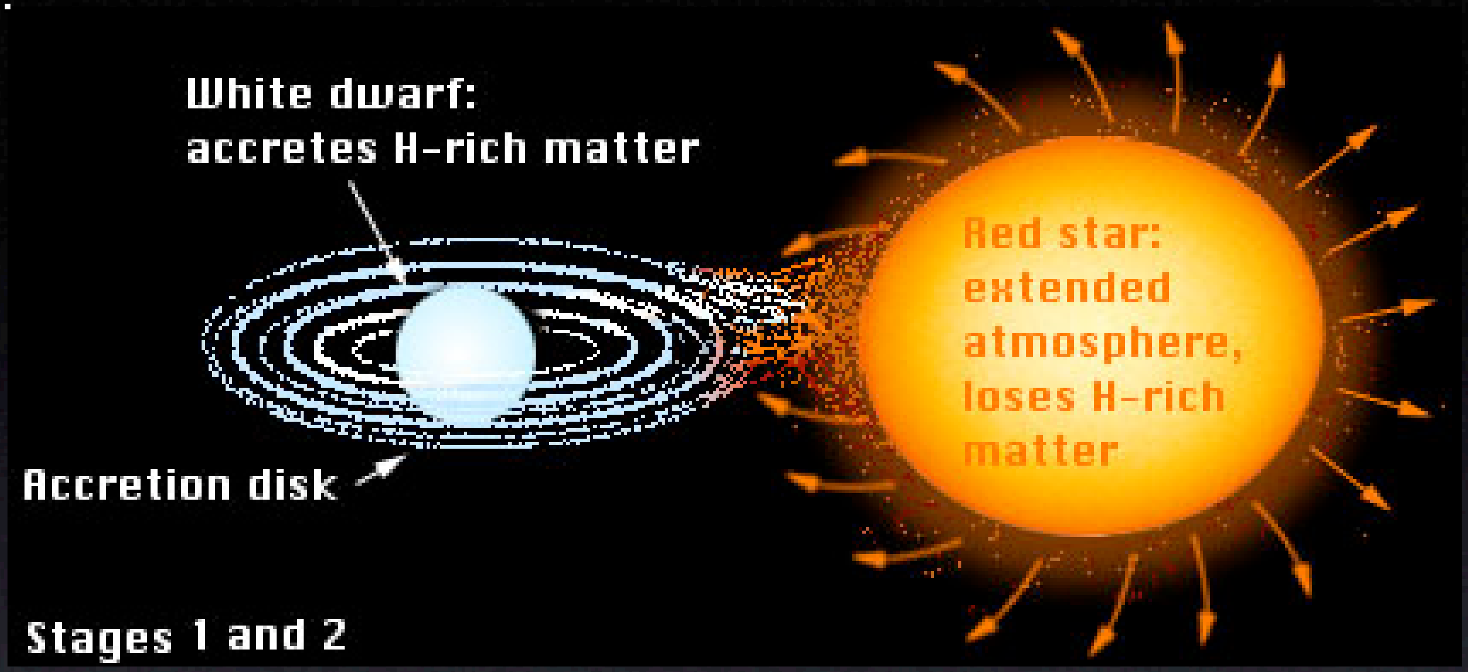
N. Miller
NASA GSFC/NRC

...and more!

Outline

- What is a Nova?
- Why Study Novae?
- Instrumentation
- Recent Observations
- Modeling Novae
- Concluding Remarks, Q&A

What is a Nova?

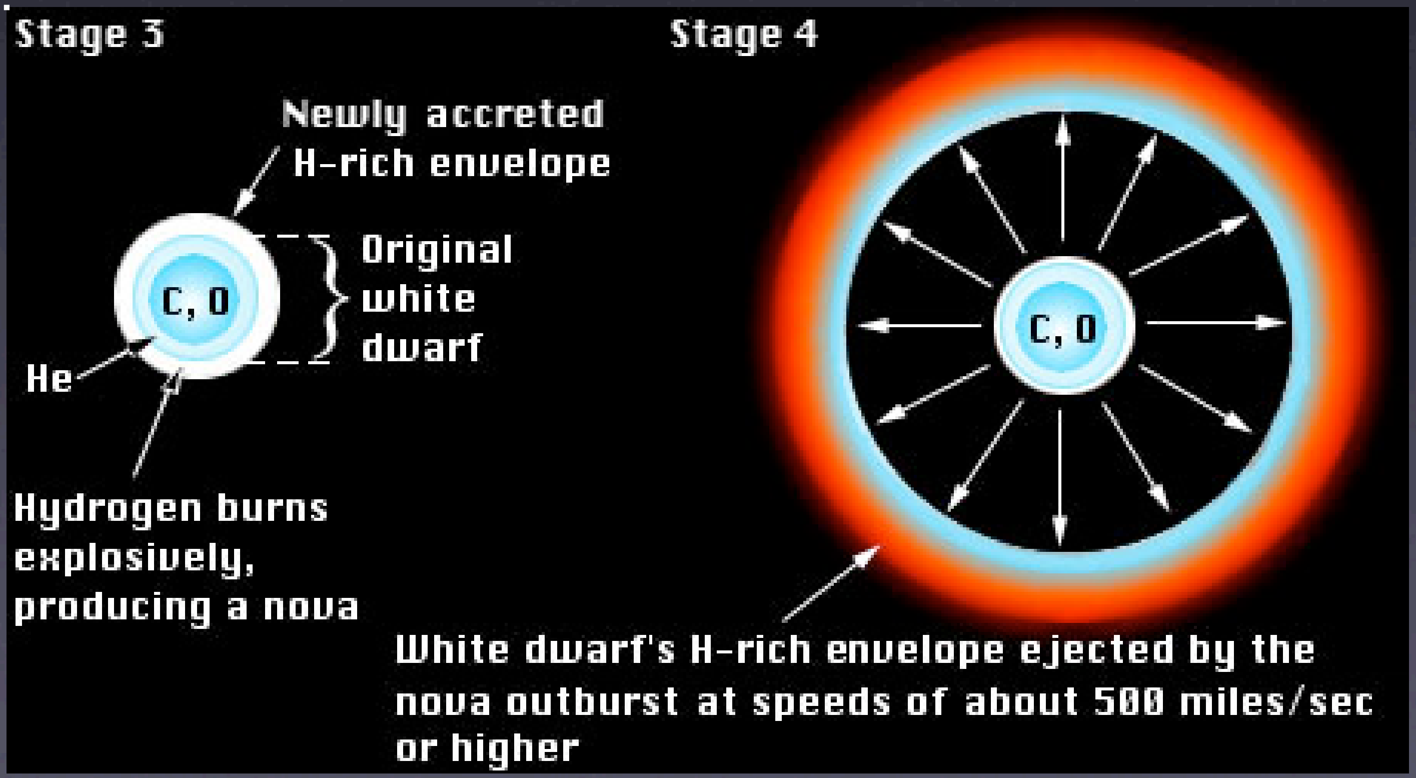


Stage 1. A white dwarf and a red star orbit each other in close proximity. The white dwarf has a core of carbon and oxygen and a thin surface layer of helium. The red star has an expanding hydrogen-rich atmosphere.

Stage 2. Much of the hydrogen-rich matter lost by the red star is captured by the white dwarf. The hydrogen-rich matter passes through an accretion disk and spirals down to the white dwarf's surface.

Stage 3. The hydrogen-rich matter accumulates on the surface of the white dwarf and eventually explodes with great violence.

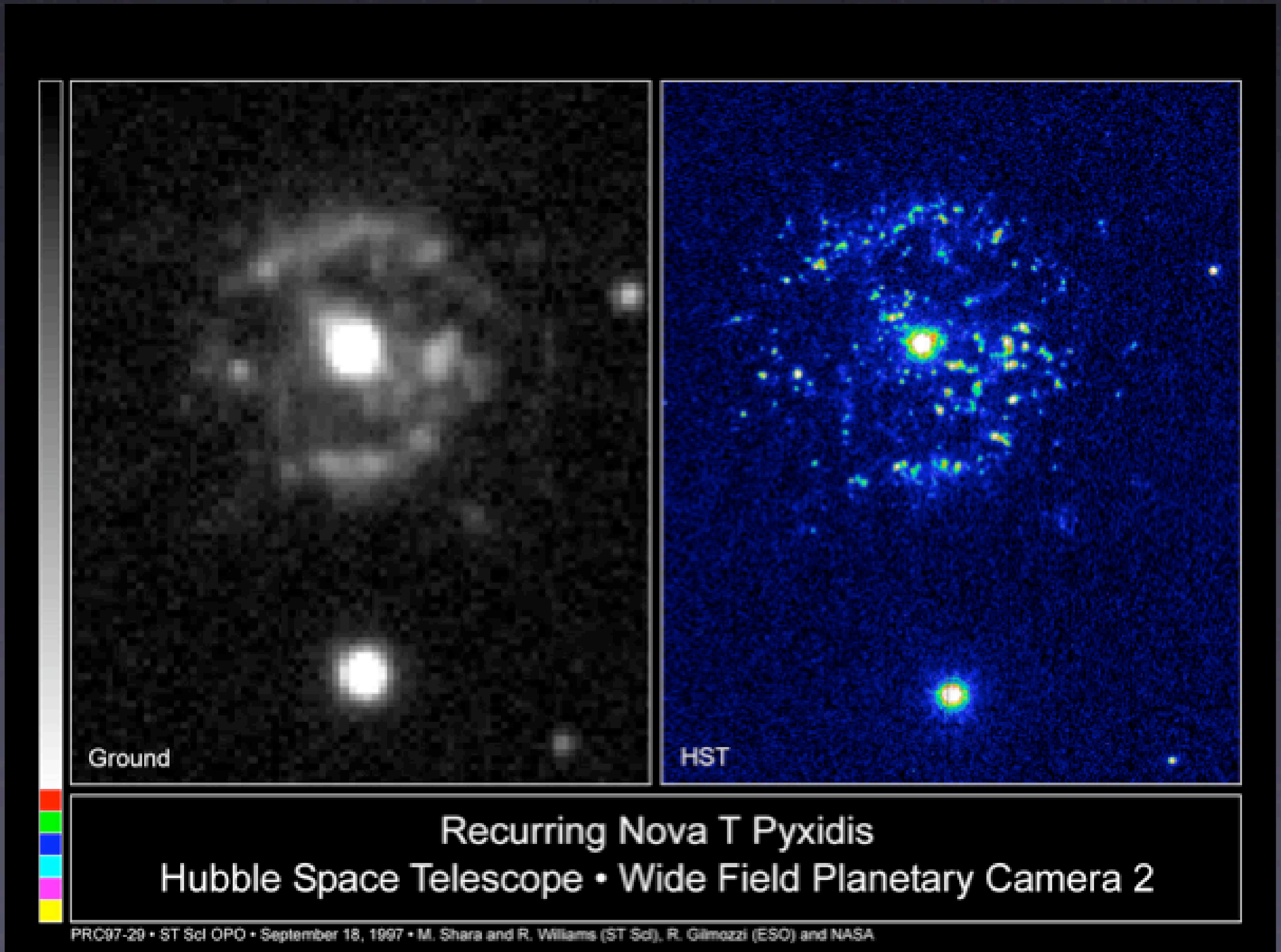
Stage 4. The explosion is the nova outburst: Rapid brightening of the white dwarf and ejection of surface material at high speeds.



Excerpt from: http://observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_4a.html

What is a Nova?

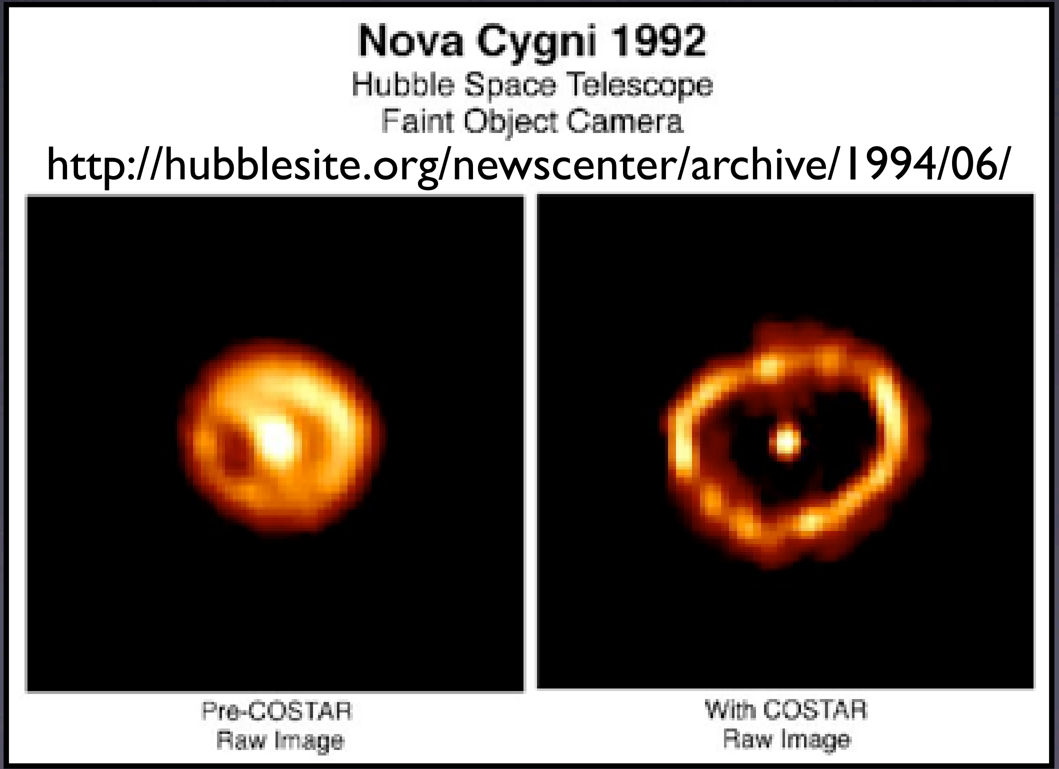
- Novae composition can be determined by spectroscopic observations
  - Ejecta combination of underlying WD and accreted material
    - Carbon-Oxygen (CO)
    - Oxygen-Neon-Magnesium (ONeMg)
- Speed class
  - Rate visual magnitude light curve decays after maximum
  - “Fast” or “Slow”



http://hubblesite.org/newscenter/archive/1997/29/

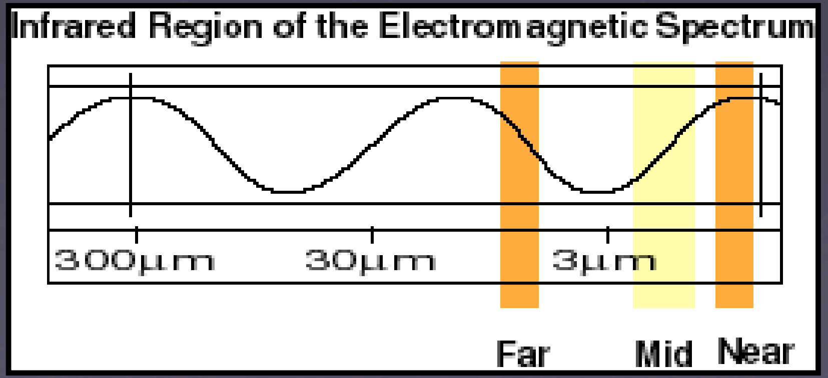
Why study Novae?

- Enrich the ISM with heavy elements
- Study galactic chemical evolution, mass transfer, and accretion phenomena in binary systems
- Good distance indicators
    - Intrinsically high luminosities
    - Correlation of absolute magnitude and rates of visual decline



Why study Novae in the IR?

- Temporal development of novae
- Reddening lower
- Resolve gas-phase formation and highly ionized emission lines and elemental abundances
- Dust
  - Chemical composition of dust condensates which may form in the cooling ejecta
  - Detect "warm" dust directly
- Study novae continuum



Limitations working in IR....

- For those working in ground-based observatories
  - Atmosphere opaque in IR spectral region
    - High altitudes "atmospheric windows"
    - Transmission increases with increasing altitude
  - Need low atmospheric emission (low airmass)
    - Atmosphere emission often orders of magnitude greater then astronomical sources
    - Introduces noise in the signal

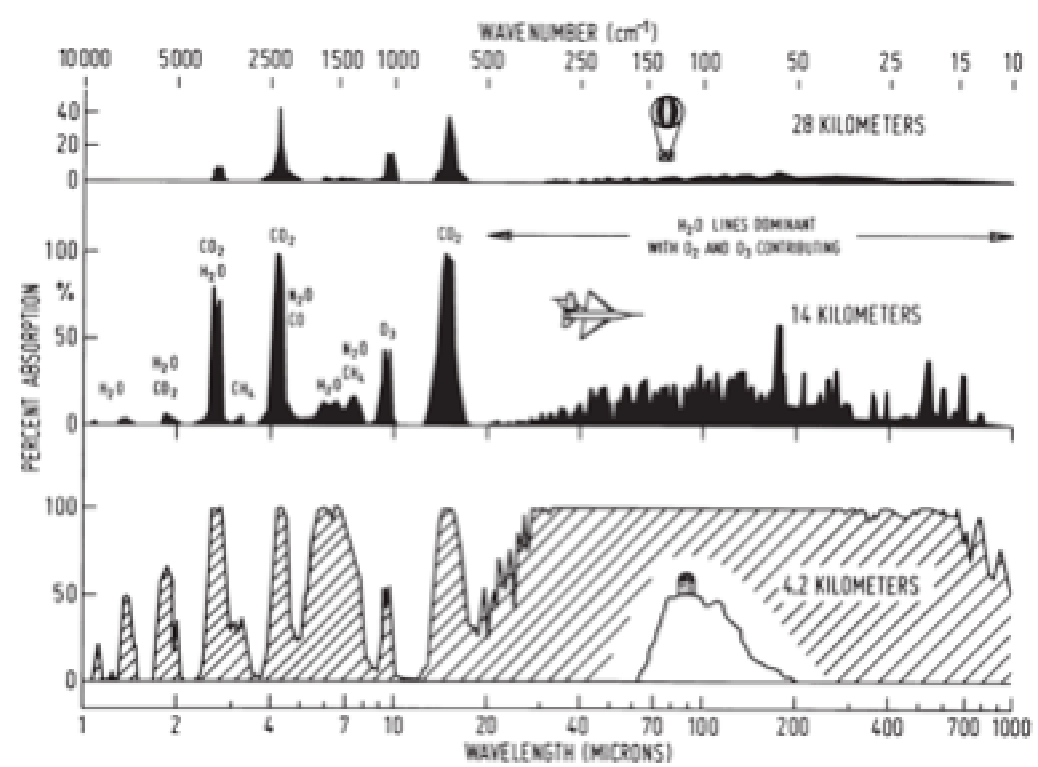


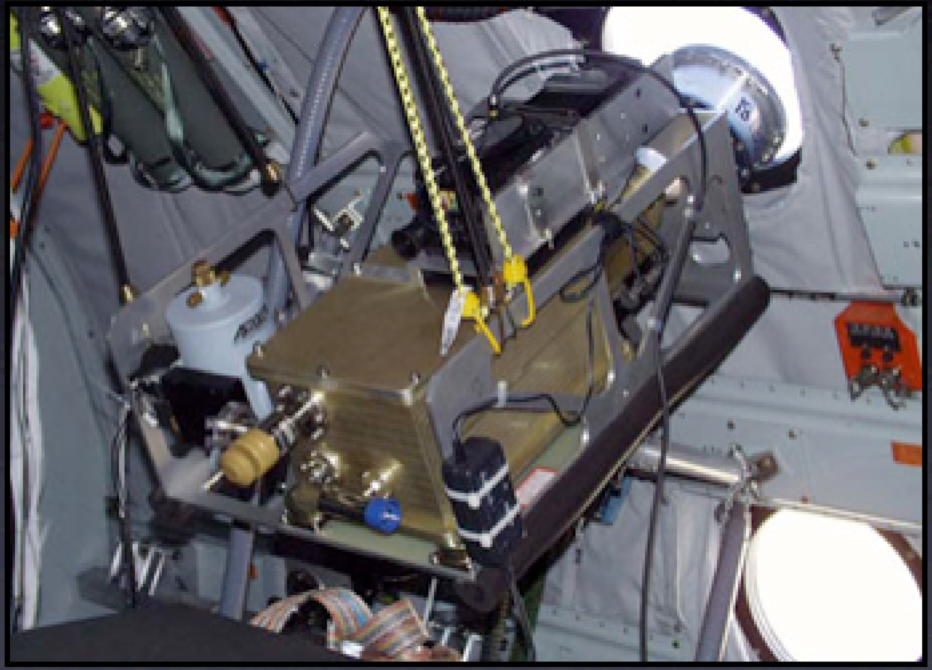
Figure 2 Atmospheric absorption in the infrared at altitudes of balloons, aircraft, and a mountain-top site like Mauna Kea (after Traub and Stier 1976).

Instrumentation

Suite of in-house IR instruments

Broadband Array Spectrograph System (BASS)
2.9-13.5   m wavelength region

Midwave Infrared Imaging Spectrograph (MIRIS)
3.0-5.5   m wavelength region

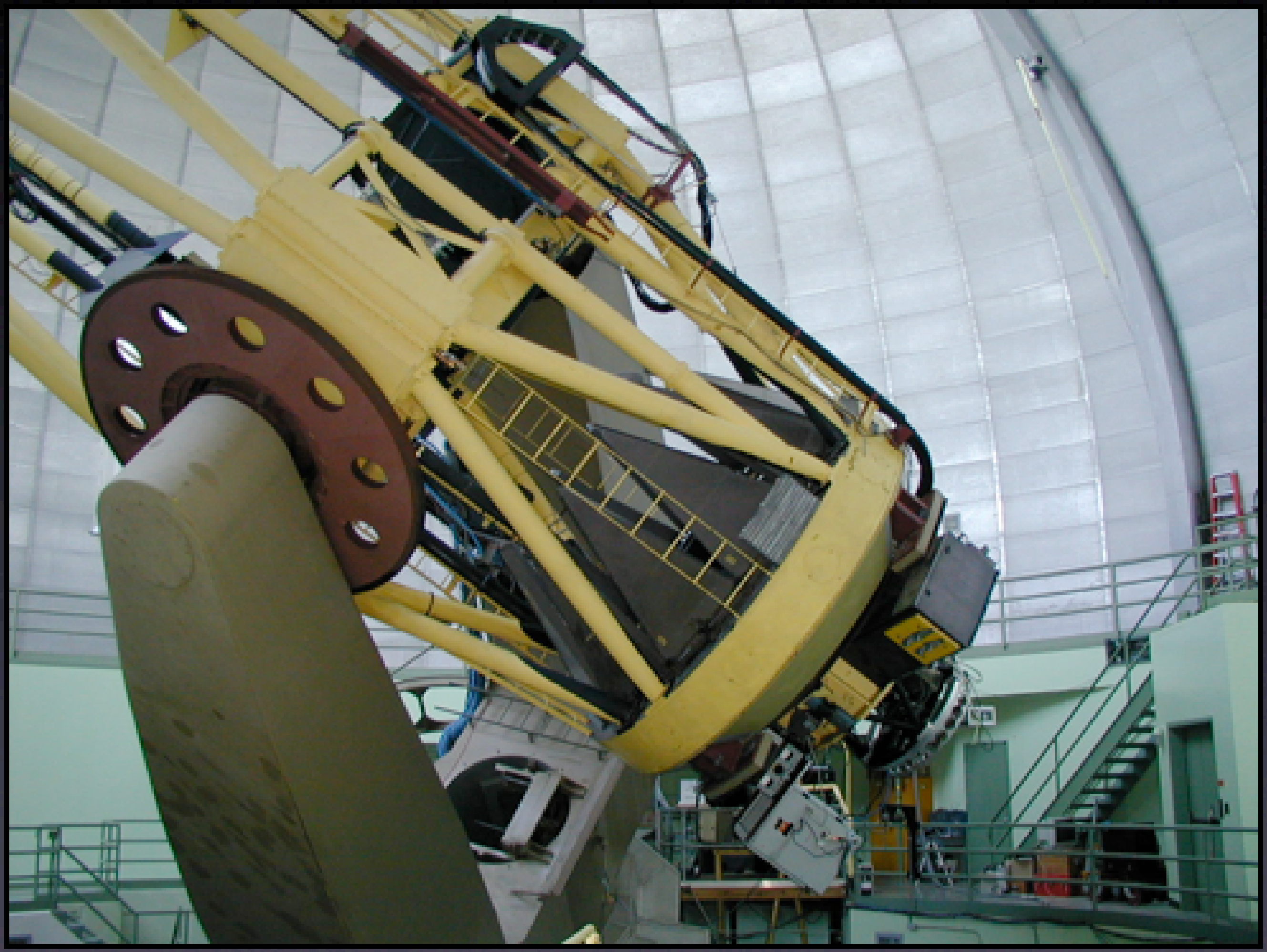


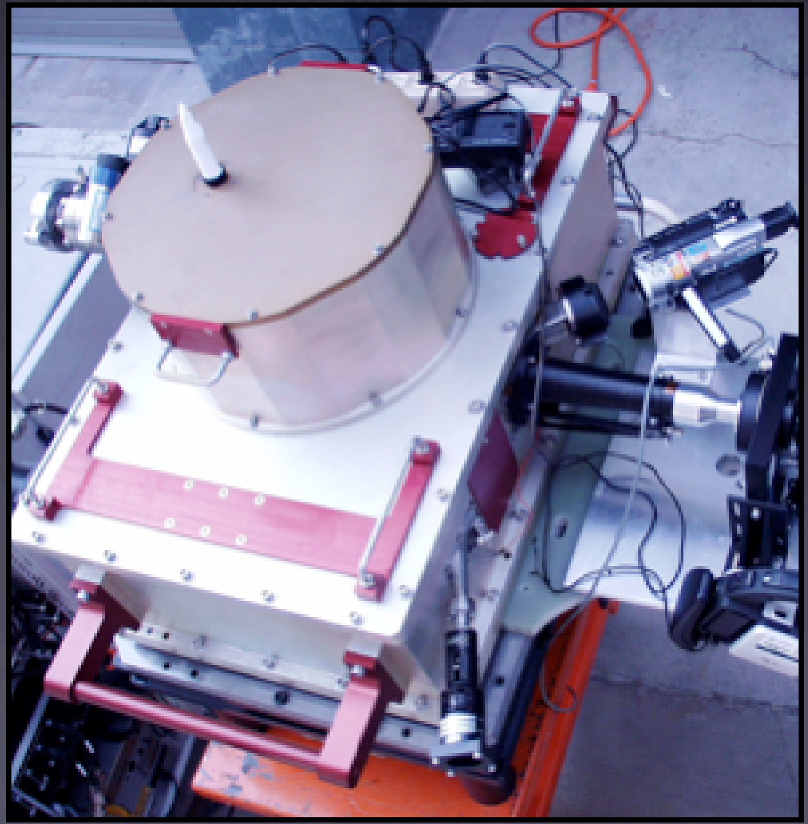
Near Infrared Imaging Spectrograph (NIRIS)
0.8-2.5   m wavelength region

Also...
Near Infrared Camera (NIC)
Aerospace Nightglow Imager (ANI)
Aerospace Multi-spectral Imager (AMI)

Instrumentation

Near Infrared Imaging Spectrograph (NIRIS)



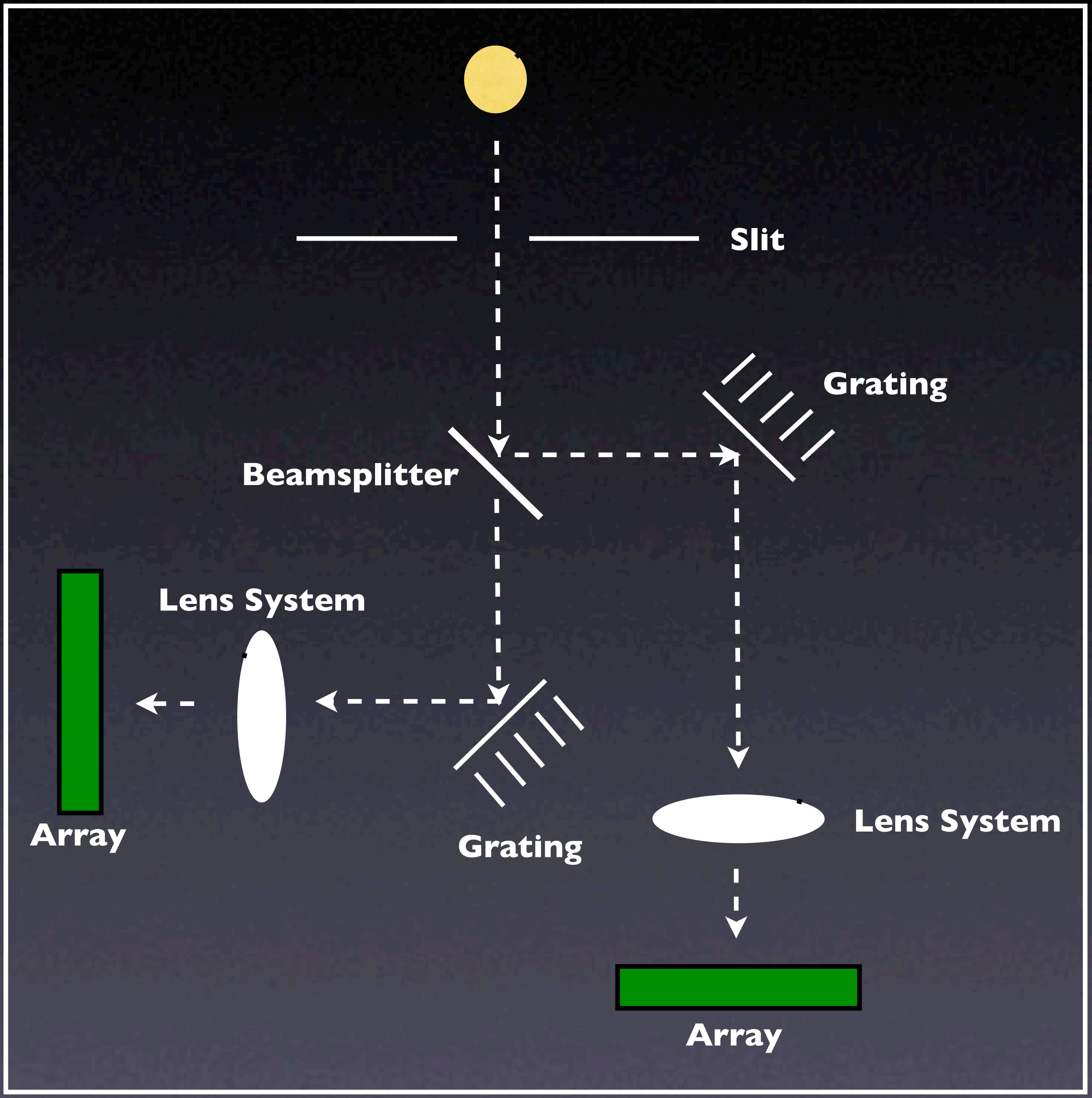


Univ. of Calif. Lick Observatory
3-m (120") Shane Telescope
Mt. Hamilton, CA
http://www.ucolick.org/

Instrumentation

Near Infrared Imaging Spectrograph (NIRIS)

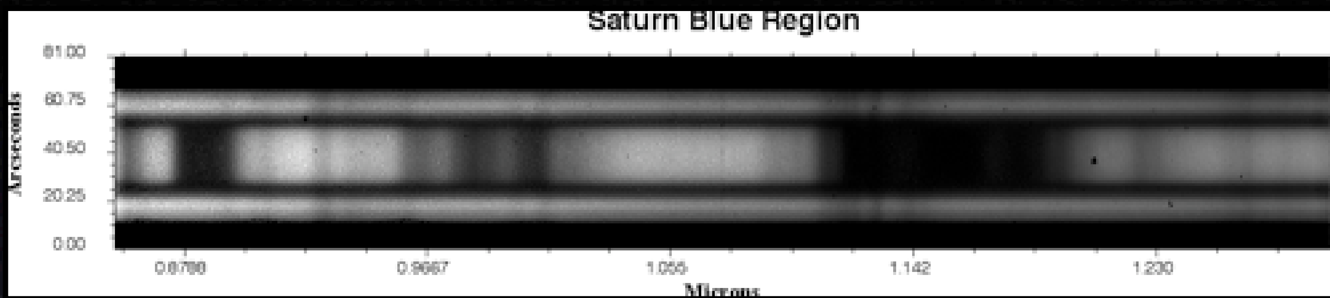
- Long-slit spectrograph
- Wavelength coverage: 0.8-2.5 m*
- Resolving power $\lambda/\Delta\lambda \approx 1000$
- Two Rockwell Hawaii I 1024x1024 HgCdTe ccd arrays
- 2048 channels spectral dimension / 512 spatial dimension
- Using a 2-arcsec wide slit: 14 Å for the blue channel and 36 Å for the red
- LN_2 cooled
- All refractive elements

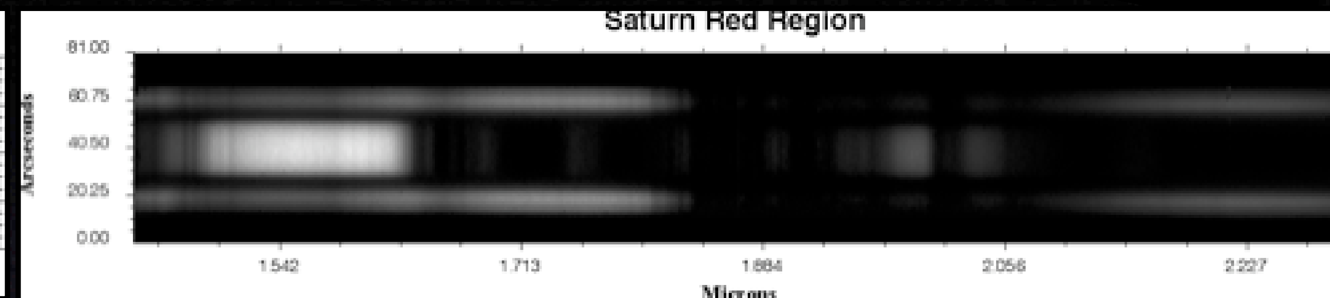


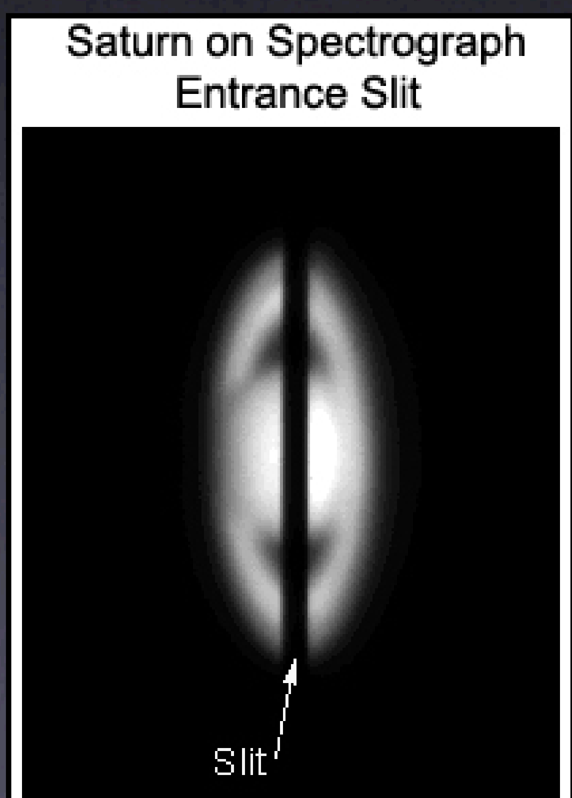
*optical camera will extend wavelength coverage to nominaly 0.4 microns (capable of UV wavelength coverage) - testing to start summer of 2003

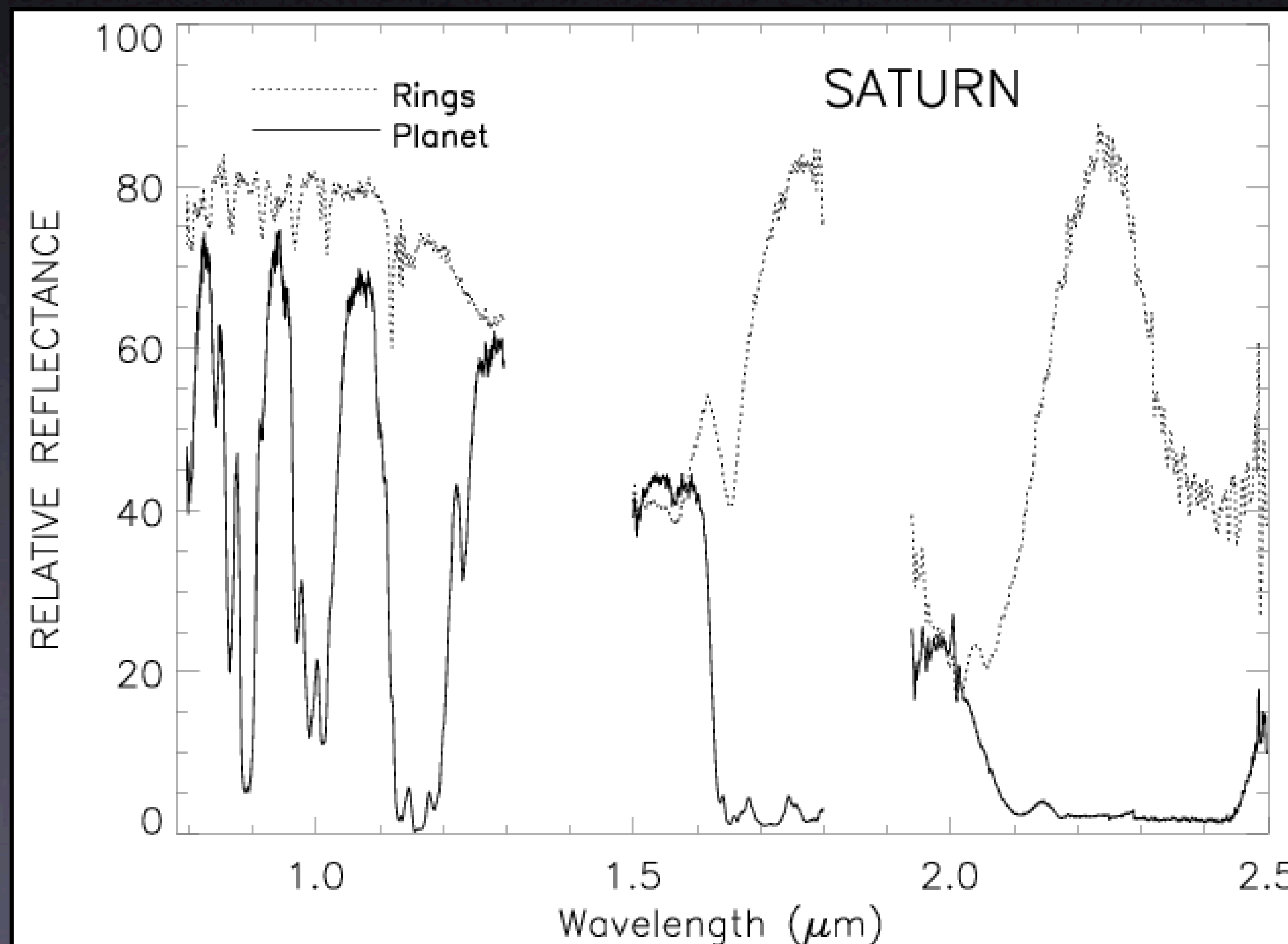
Instrumentation

Near Infrared Imaging Spectrograph (NIRIS)



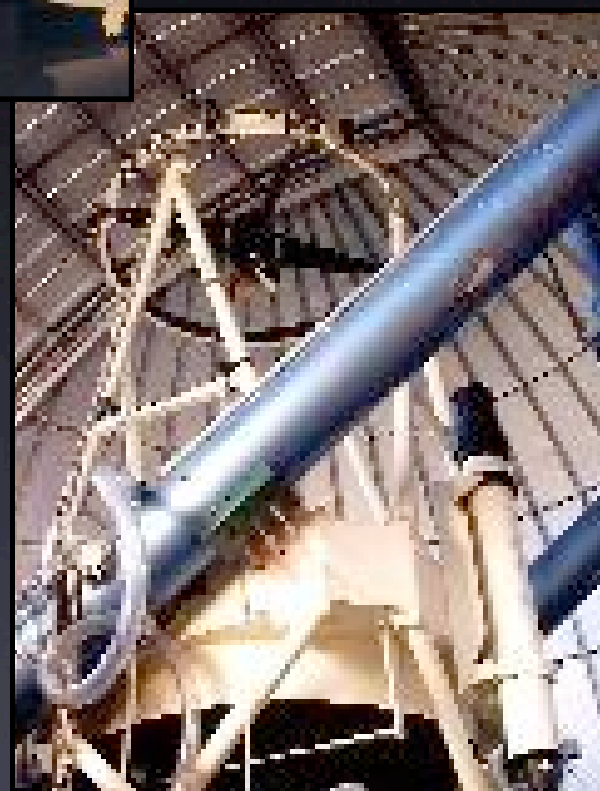




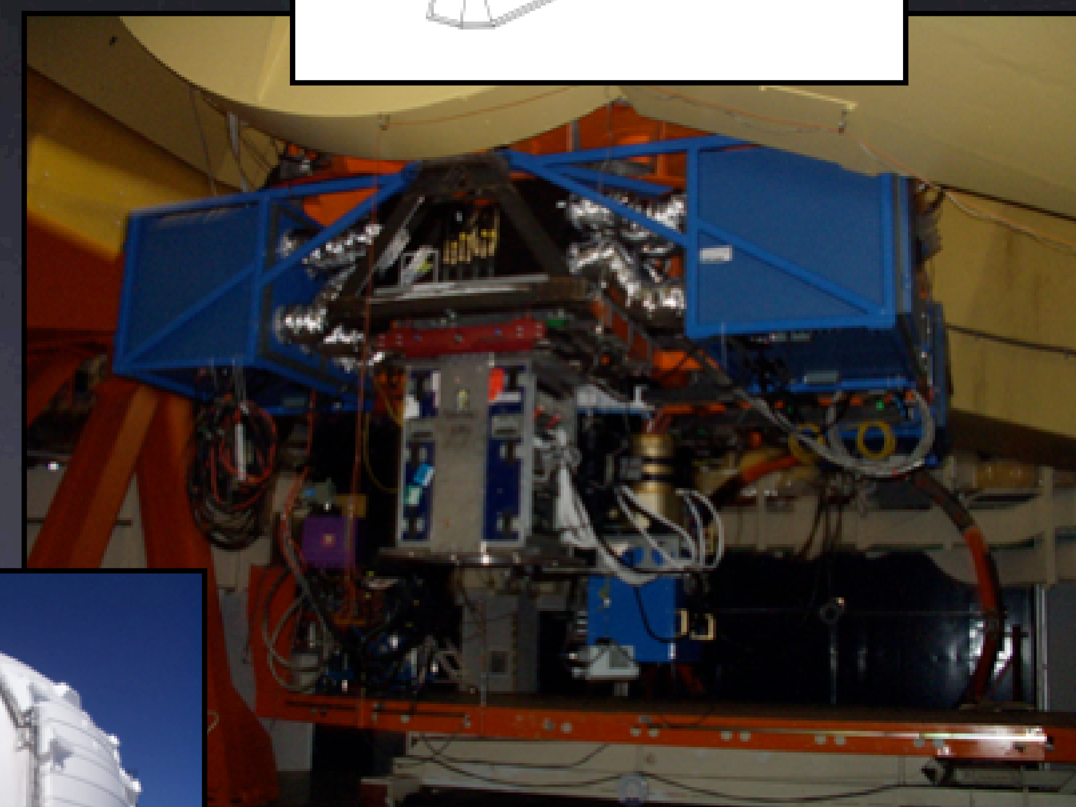


Instrumentation

Broadband Array Spectrograph System (BASS)



Mt. Lemmon Observing Facility (MLOF)
near Tucson, AZ
http://www.astro.umn.edu/~lyke/mlof.html



NASA IRTF 3-M Telescope
Mauna Kea, HI
http://irtfweb.ifa.hawaii.edu/

Instrumentation

Broadband Array Spectrograph System (BASS)

- Prism spectrograph
- Wavelength coverage: 2.9-13.5 m
- Resolving power of 25-120 depending on wavelength
- Two 58 element Blocked Impurity Band (BIB) linear arrays
- Liquid Helium cooled
- Circular entrance aperture - 2 mm in diameter

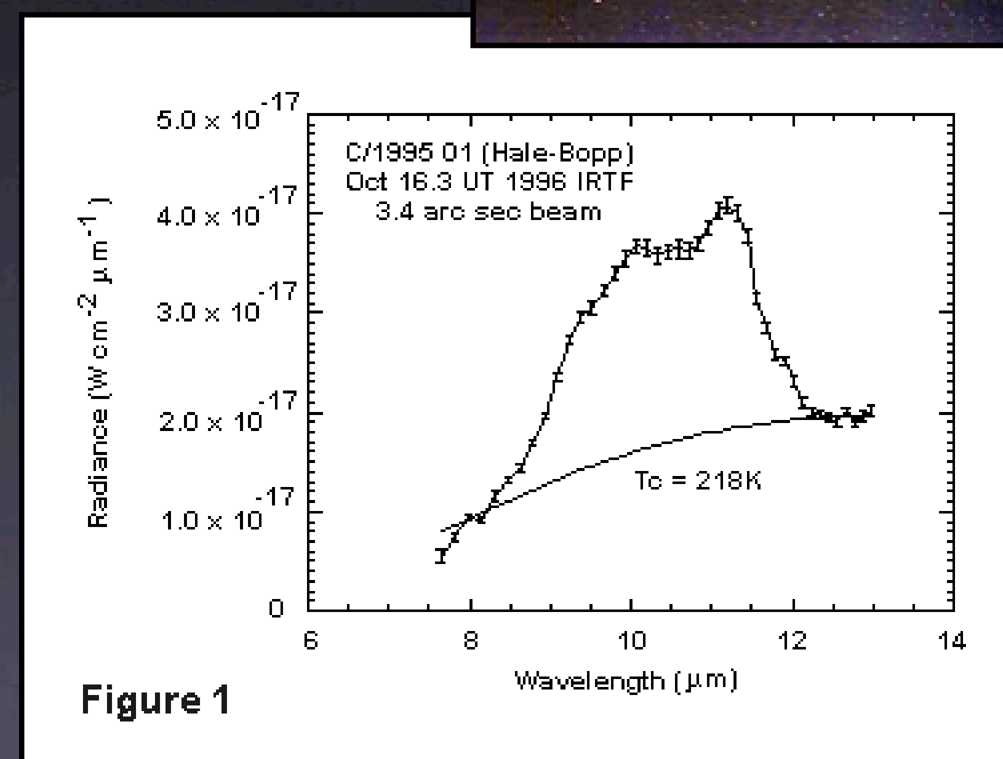


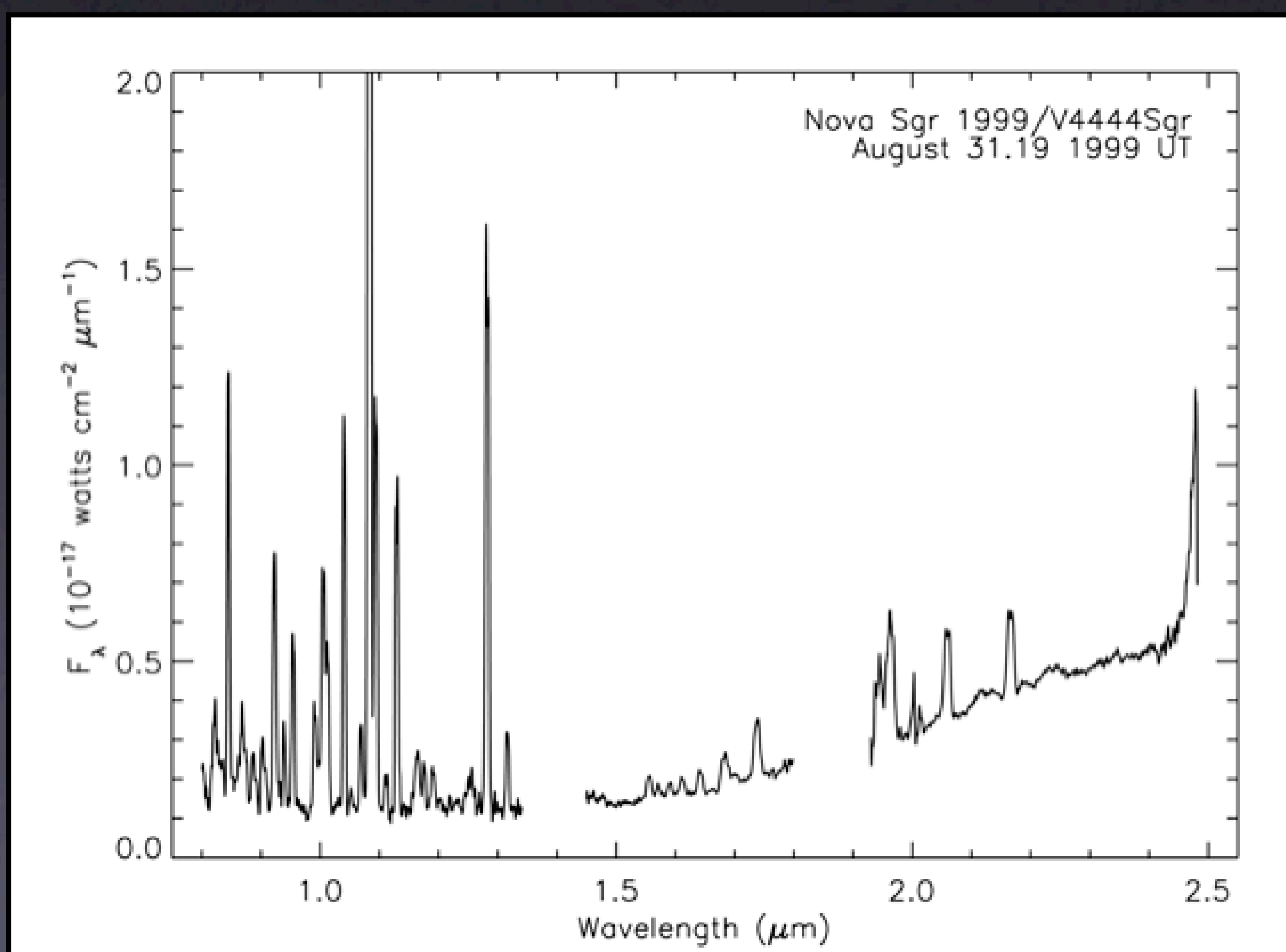
Figure 1

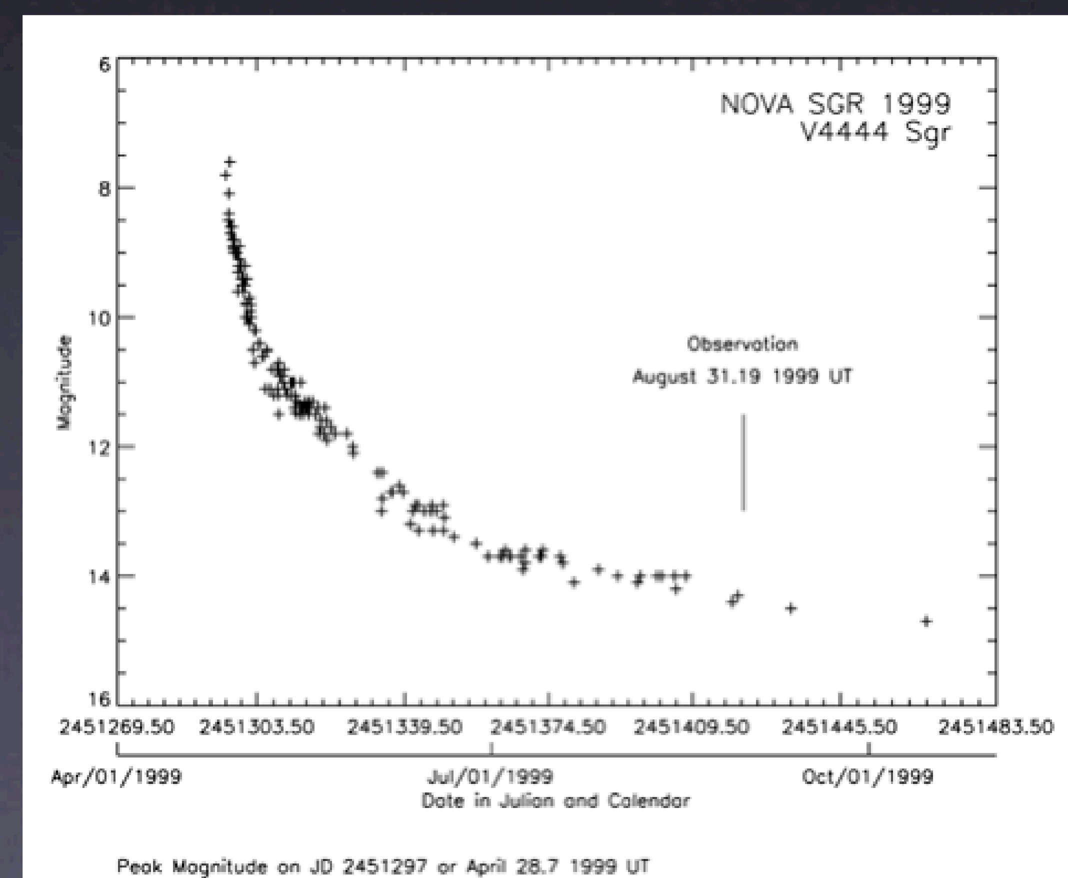
Spectrum of Hale Bopp. The spectrum shows structured silicate emission characteristic of amorphous and crystalline silicates, namely olivine and pyroxene (See Hanner et al. 1999)

Recent IR Observations
with
NIRIS and BASS

Nova Sgr 1999 - V4444 Sgr

- Very fast nova
- Discovered April 25.731 1999 UT - observed 125 days after peak outburst
- Continnum - evidence of thermal emission from dust
  - Pre-existing dust since not present in light curve or unobscured line of sight?

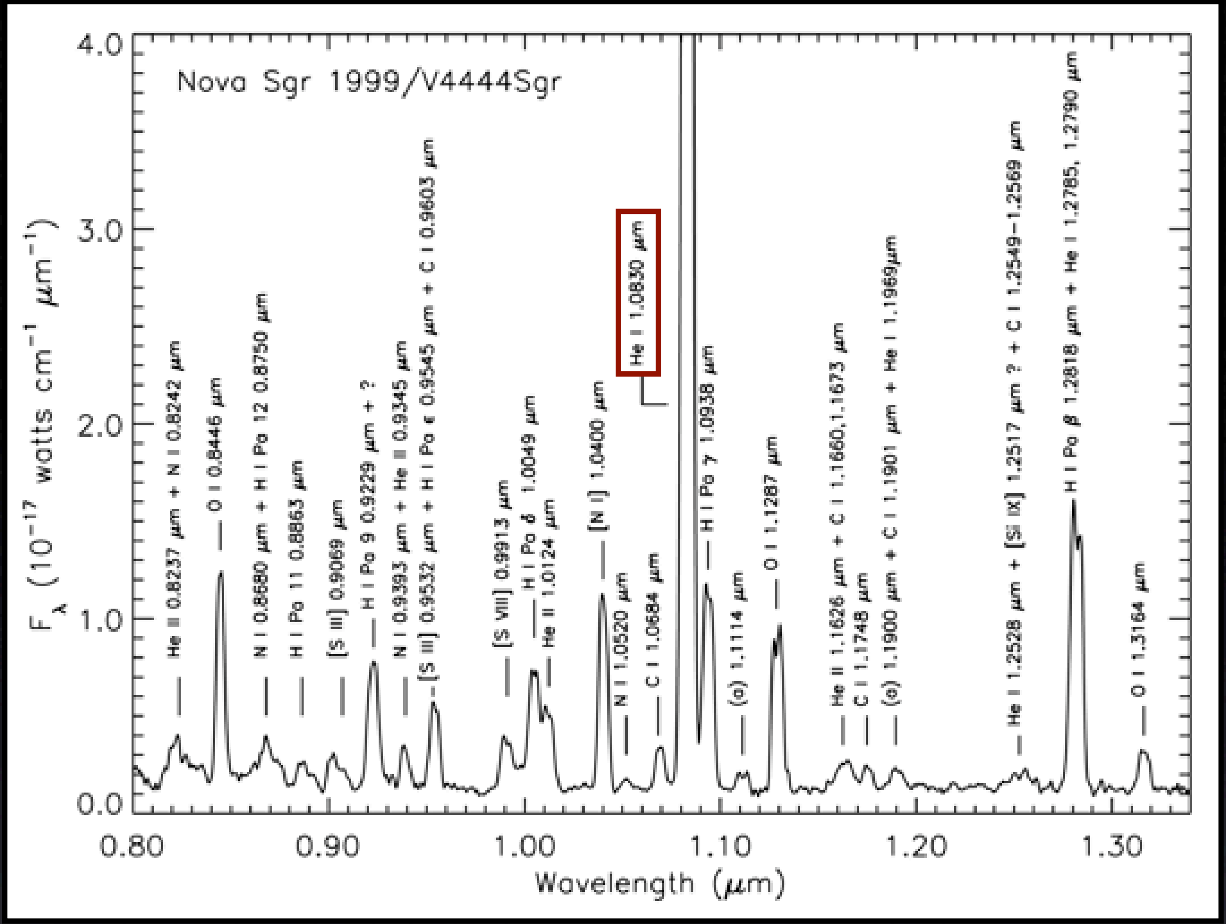


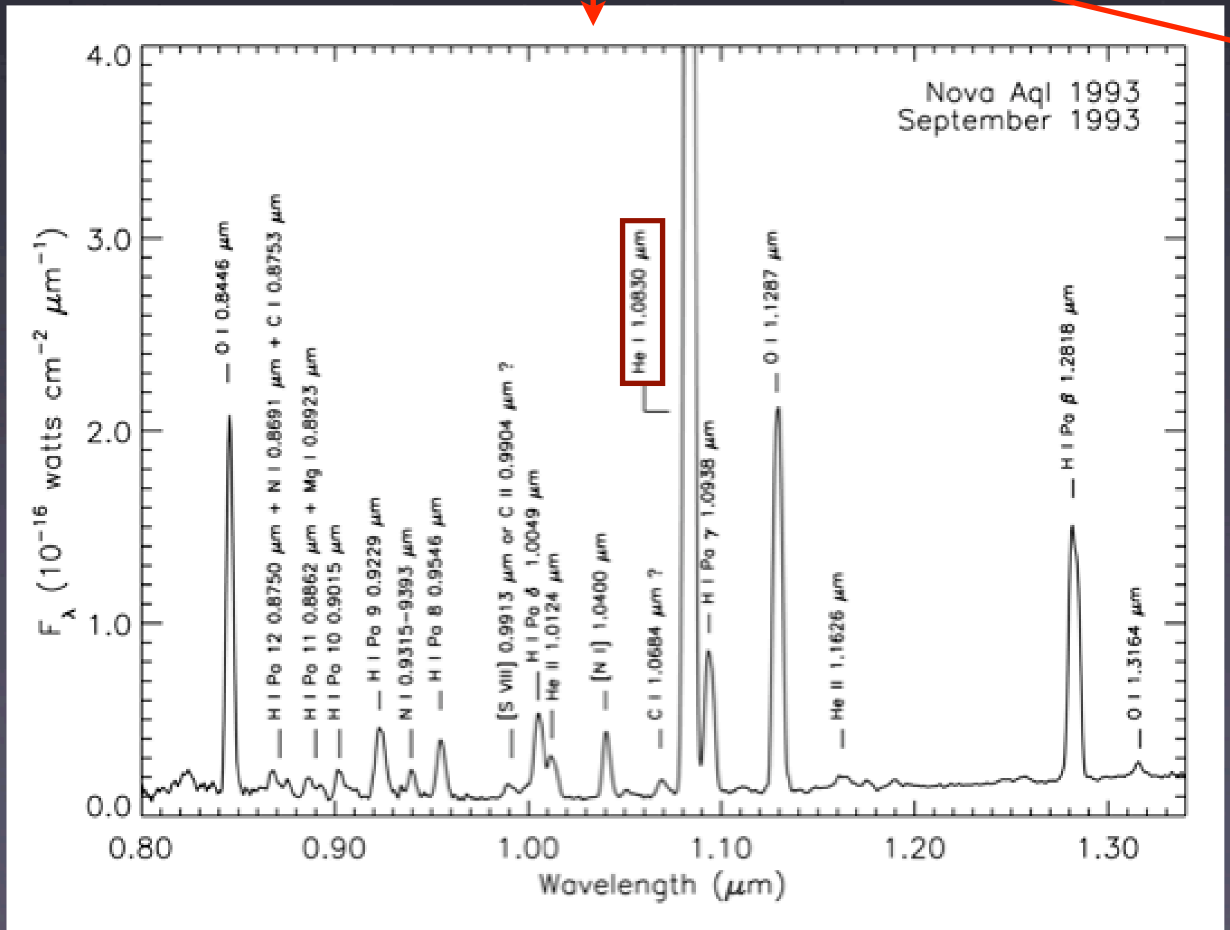


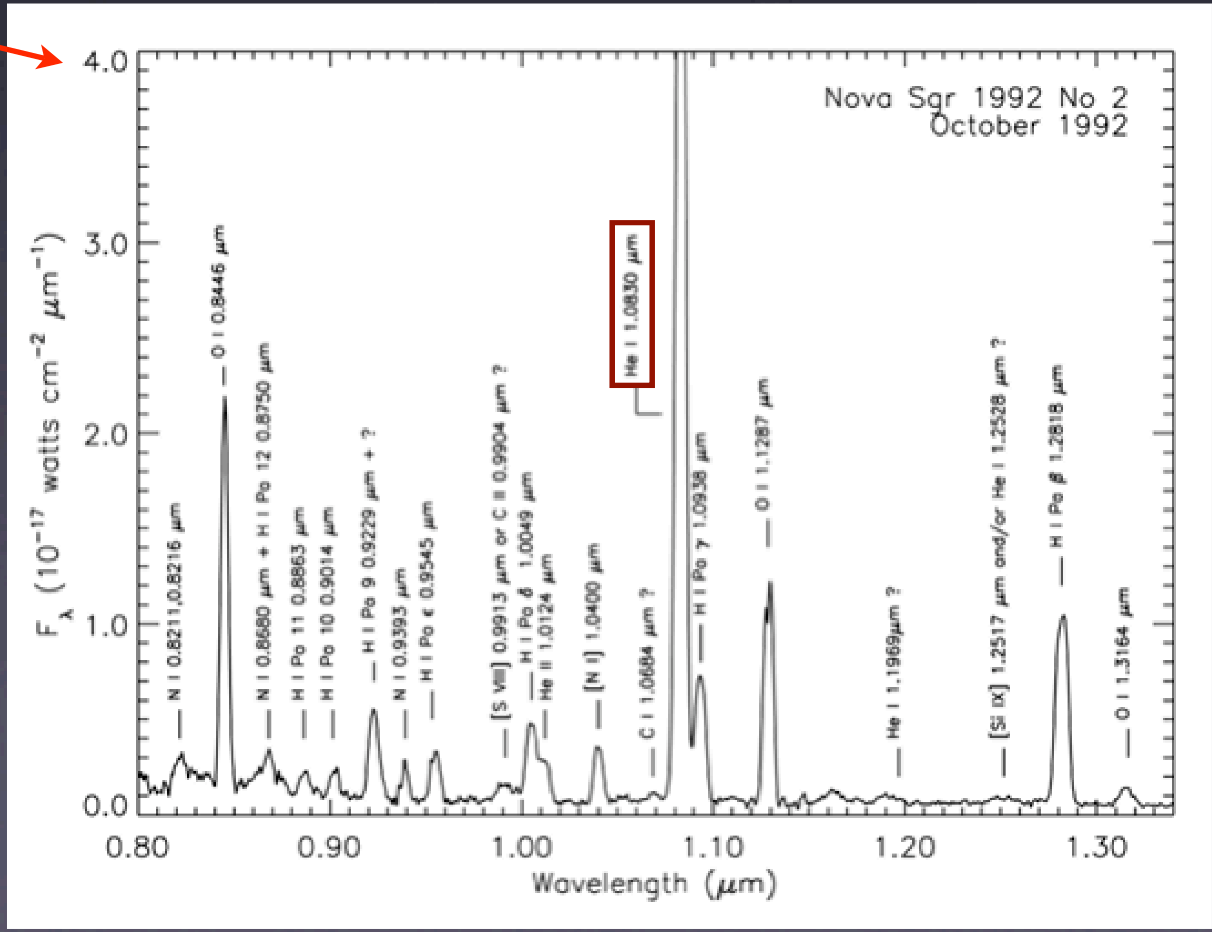
Venturini, C.C., Rudy, R.J., Lynch, D.K., Mazuk, S., Puetter, R.C., Astron. J., 124, 3009-3013, 2002

Nova Sgr 1999 - V4444 Sgr

- V4444 Sgr spectrum exhibited greatest spread of emission line excitation
- Unique yet not uncommon





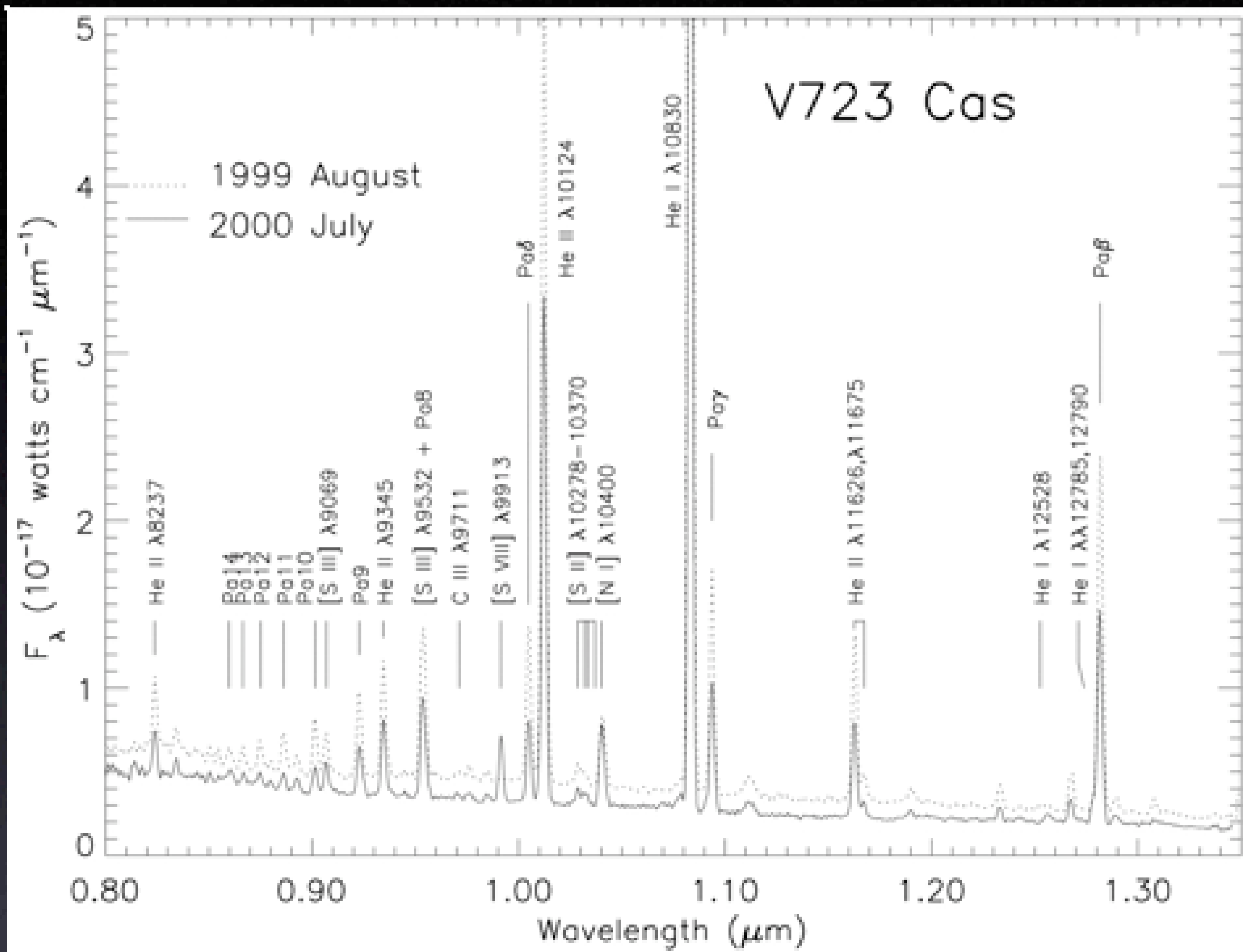


Nova Cas 1995 - V723 Cas

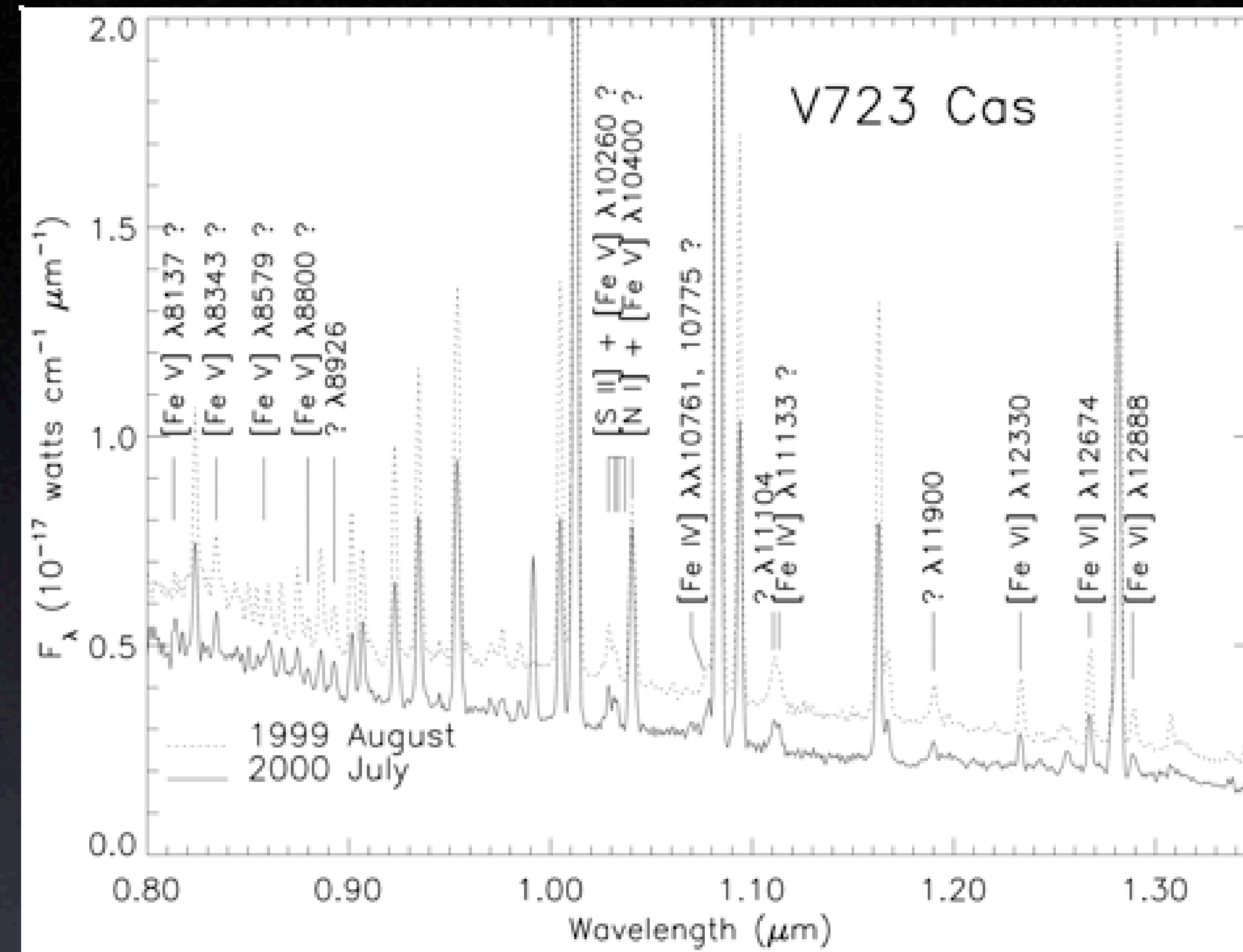
- Observed in 1999 and in 2000
- Slow nova
  - Sustained a high excitation for a long duration - able to observe 4 and 5 yrs after outburst
- Bright, narrow lines (FWHM ~ 500 km/sec) made it ideal for observing emission lines that appear in the nebular/coronal stages of novae.
  - Later stage of novae evolution when the ejecta disperses and higher excitation lines or "coronal" lines emerge
  - Fine-structure transitions to the ground energy level for species whose ionization energies are greater than 100 eV - most dramatic and unusual emisson lines in the spectra of novae
  - Provides knowledge about the conditions within the line forming regions as well as abundance information about the compact star, its companion, and the explosion process itself.
- 16 previously unobserved or unidentified features were in the spectrum
  - include lines from [Fe IV], [Fe V], [Fe VI], and [Ti VIII]

Rudy, R.J., Venturini, C.C., Lynch, D.K., Mazuk, S., Puetter, R.C., Astrophys. J., 573, 794-802, 2002

Nova Cas 1995 - V723 Cas

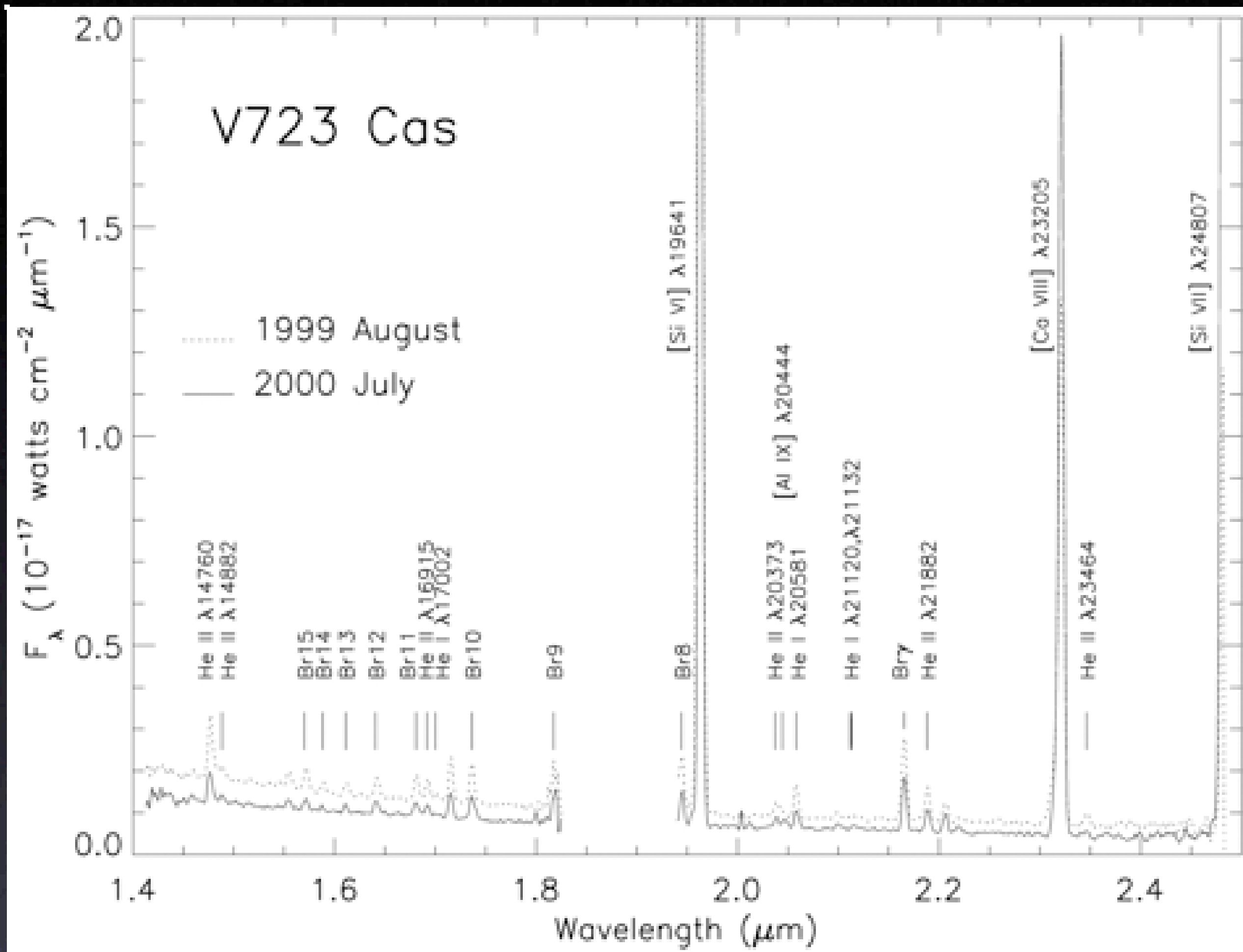


1999 August and 2000 July spectra of V723 Cas from 0.8 to 1.35 microns. All known lines previously identified in novae or planetary nebulae are labeled.

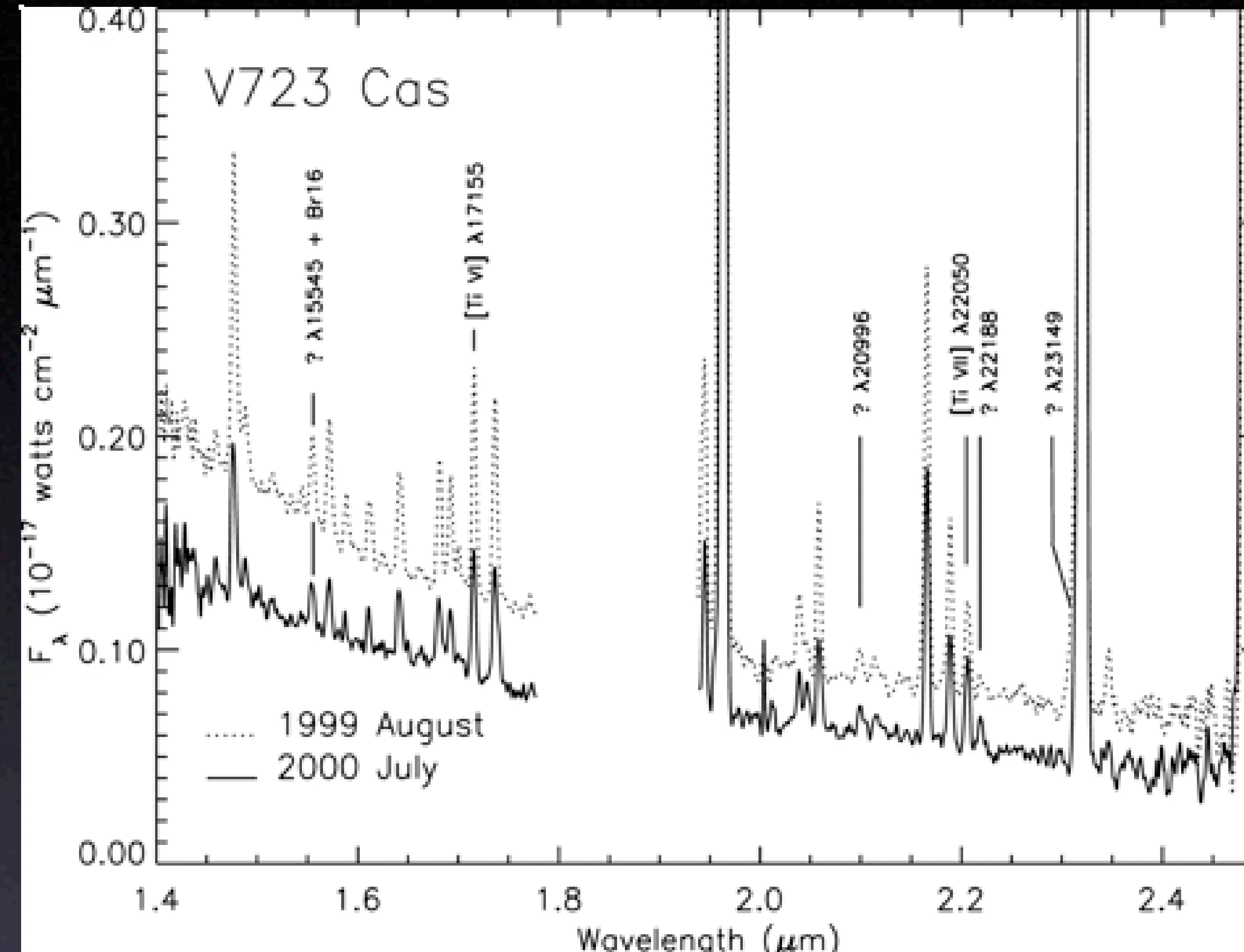


1999 August and 2000 July spectra of V723 Cas from 0.8 to 1.35 microns with the new and unidentified lines labeled. Lines with question marks either remain unidentified or have an identification that is uncertain. The presence of the [Fe v] features λλ8579, 10260, and 10400, which share the same upper level as λ8800, are masked by other emission lines. The unidentified features at 8926, 11104, 11133, and 11900 Å have been seen in other novae.

Nova Cas 1995 - V723 Cas

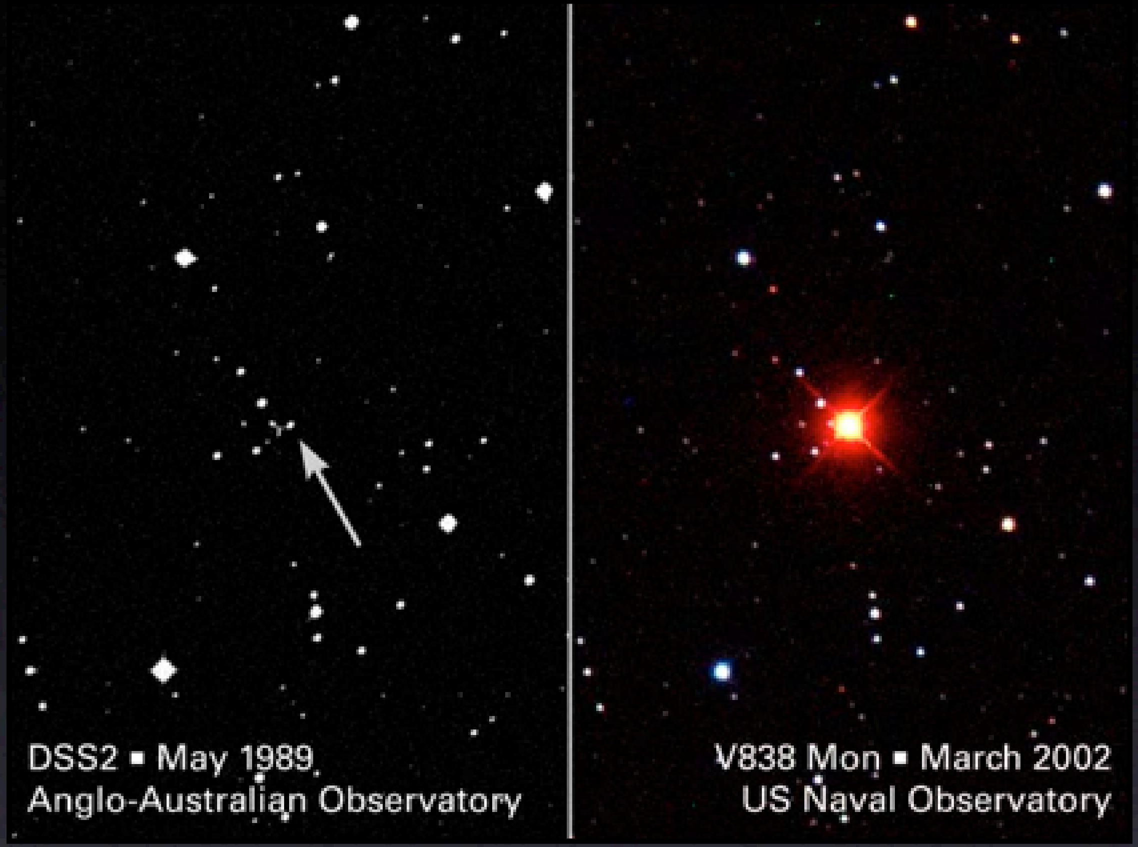


1999 August and 2000 July spectra of V723 Cas from 1.4 to 2.5 microns. All known lines previously identified in novae or planetary nebulae are labeled.

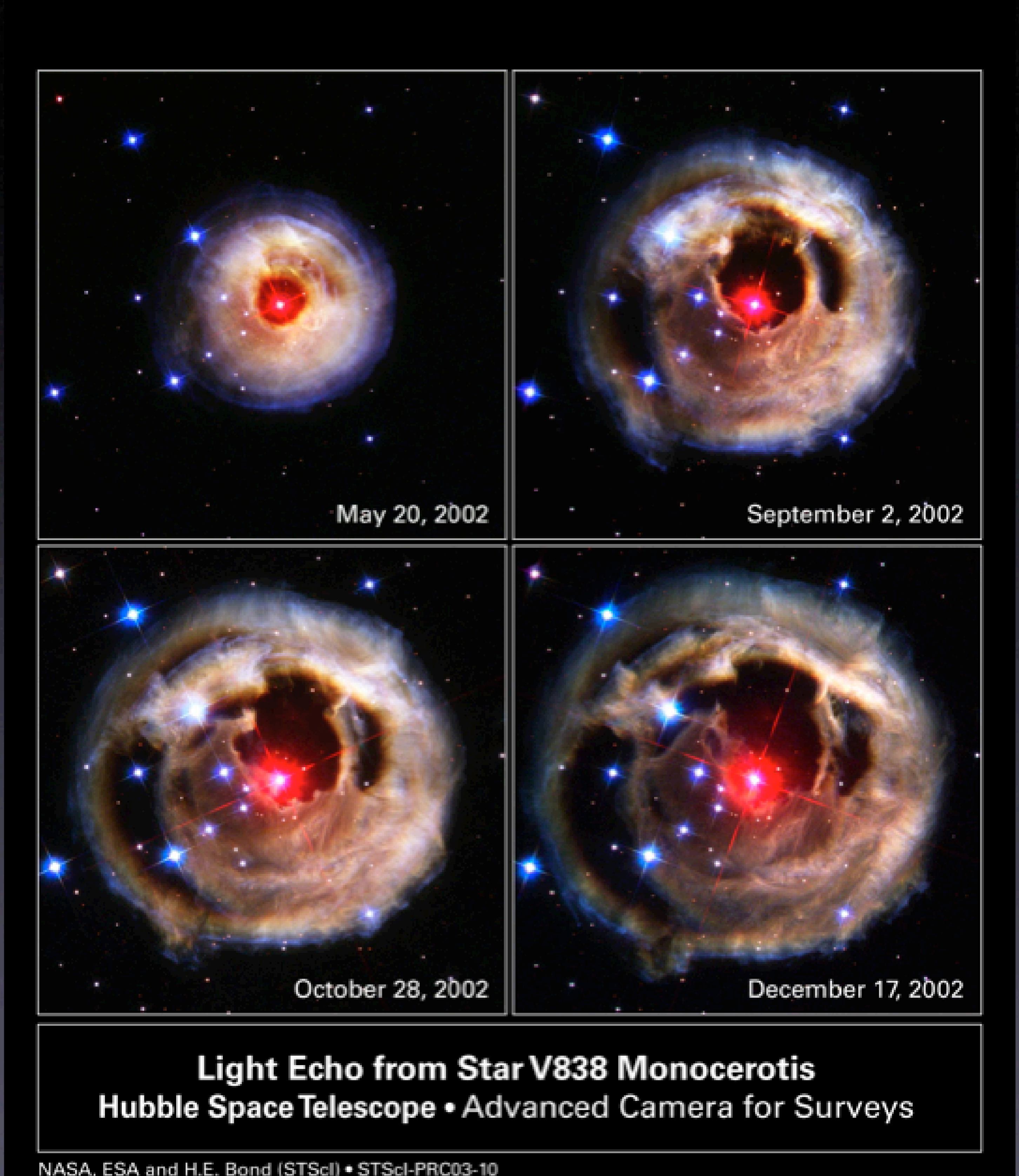


1999 August and 2000 July spectra of V723 Cas from 1.4 to 2.5 microns showing the new and unidentified lines. The [Ti VI] λ17155 line, discovered previously in V1974 Cygni (Nova Cygni 1992), is shown for comparison with the newly detected [Ti VII] λ22050 feature. Lines with question marks either remain unidentified or have an identification that is uncertain. The features at 15545 and 20996 Å have been in other novae.

Mysterious Object - V838 Monocerotis



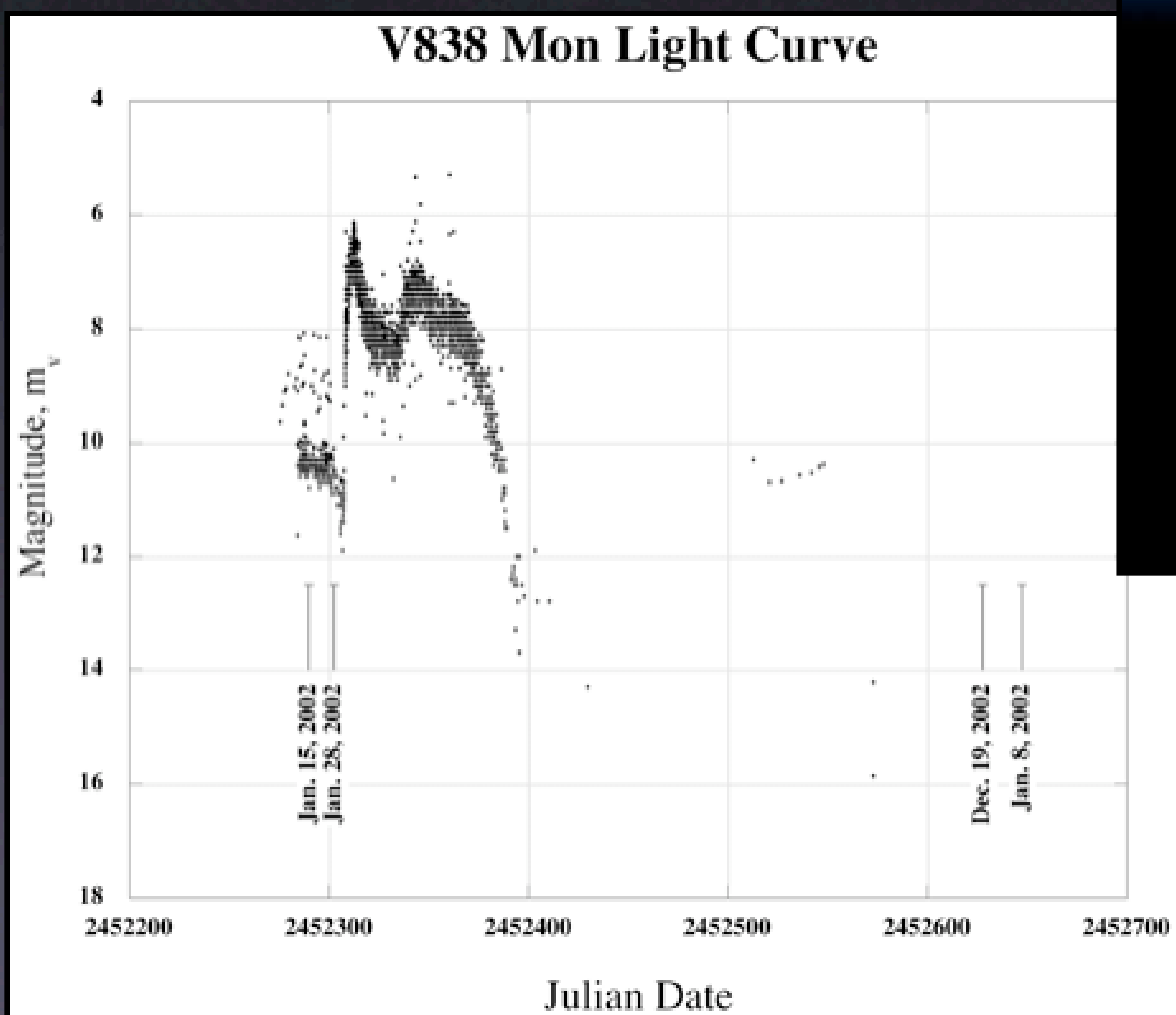
- Discovered Jan 2002
    - Prior to outburst - a hot (7300K) blue star
    - At one point brightest object in the sky
- Light echo discovered in Feb 2002
    - due to dust around V838 Mon
- Distance ~20,000 light-years or ~6 Kpc

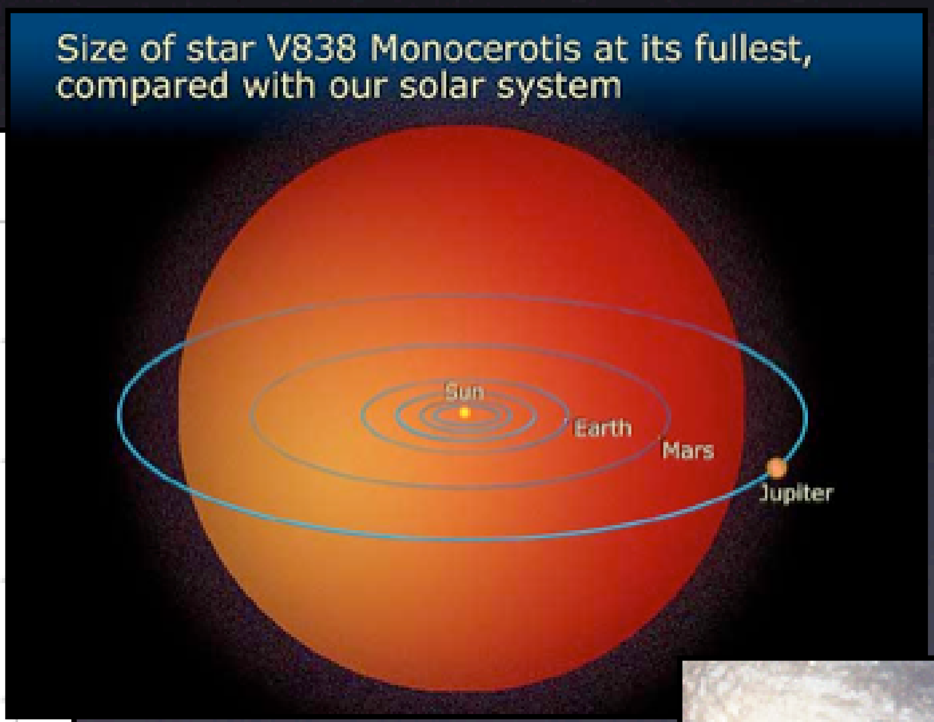


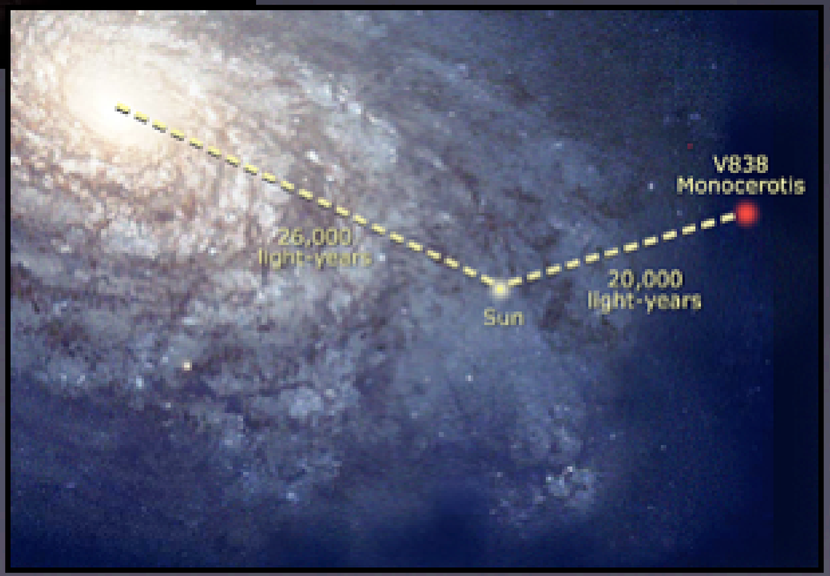
http://hubblesite.org/newscenter/archive/2003/10/

Mysterious Object - V838 Monocerotis

- Less than a year underwent a series of major photometric outburts
  - Lower temperature (6000K to 2000K and less)
  - Larger luminosity (power output)
- Outburst similar to novae except did not expel its outer layers - instead grew enormous in size
- Due to unique evolution - represent a new class of objects called "stars erupting into cool supergiants" (SECS)

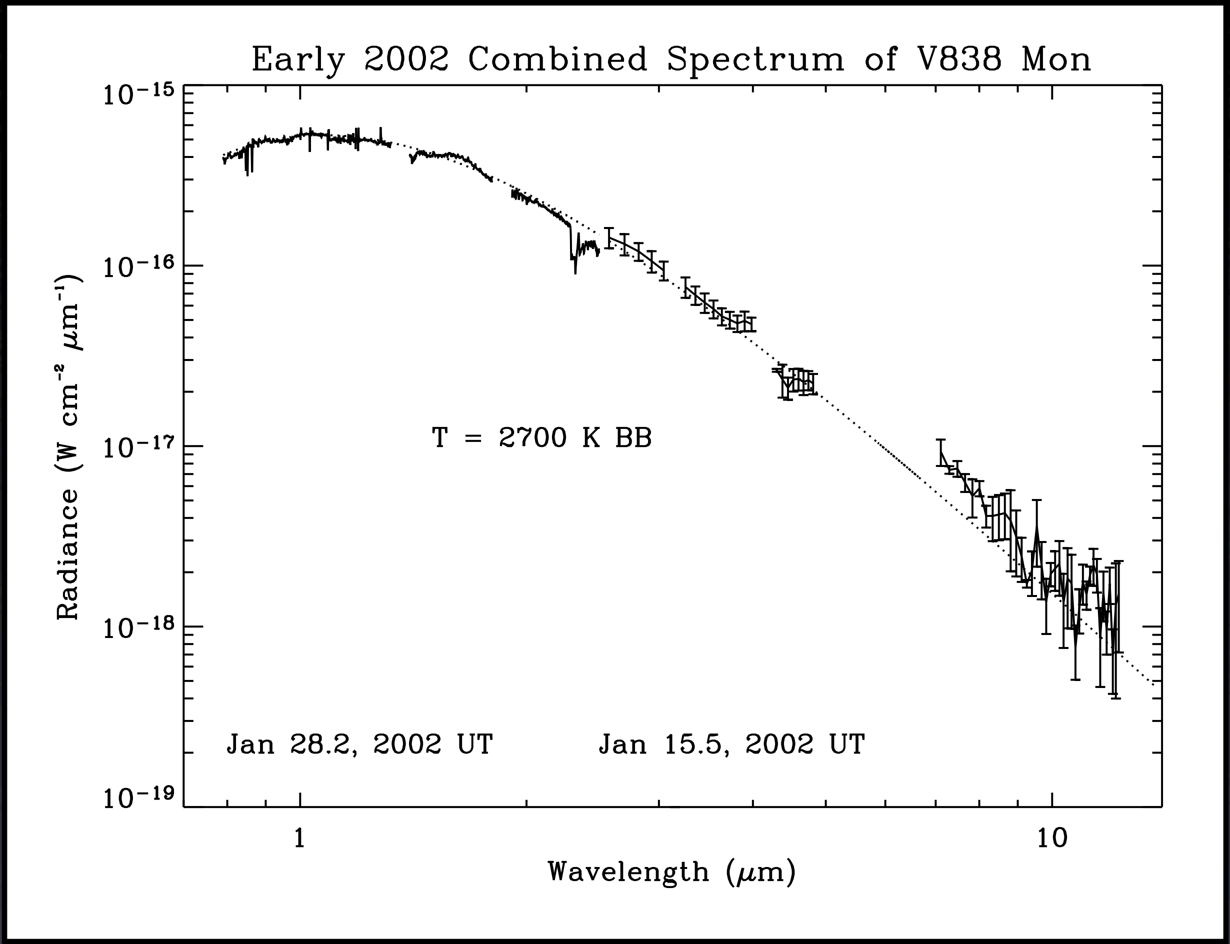


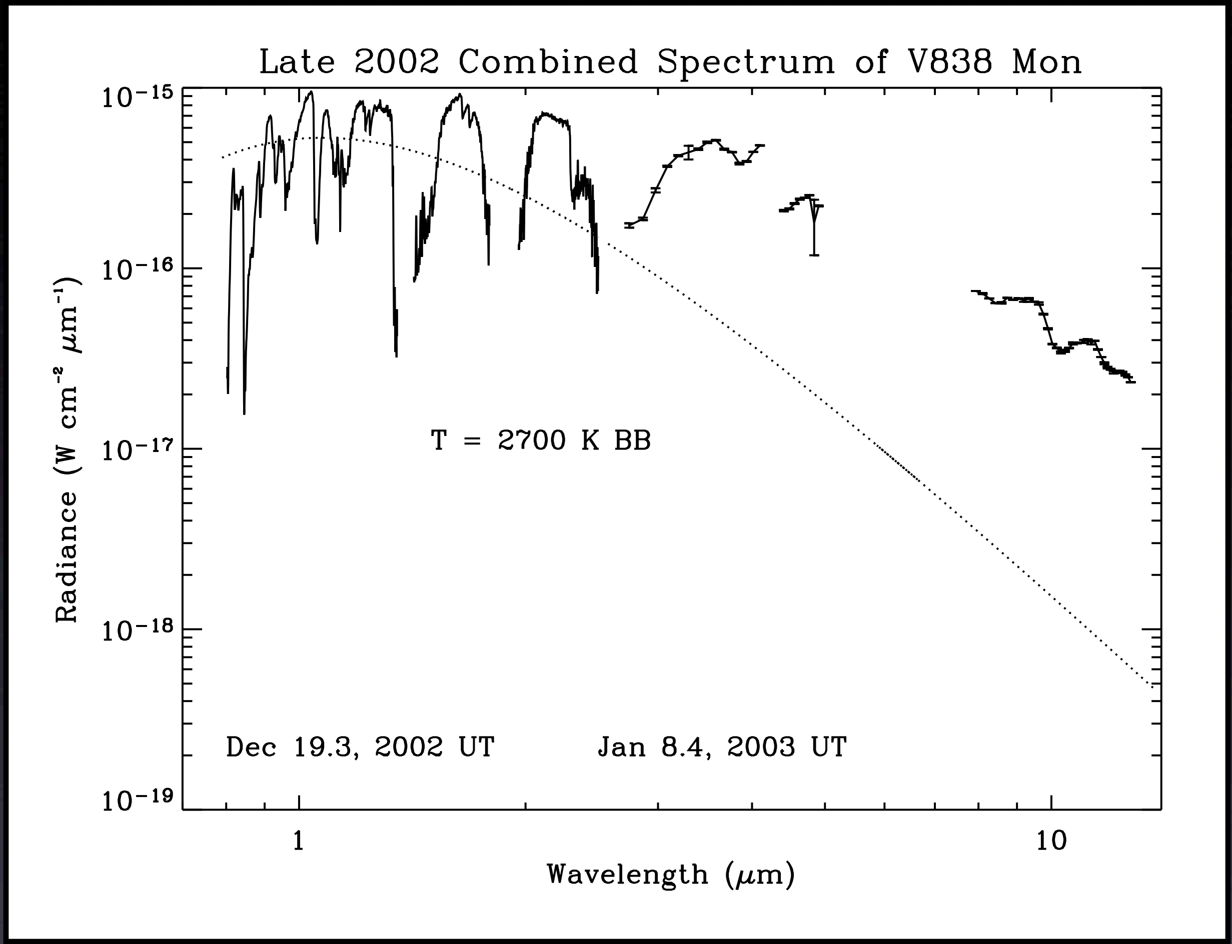




Mysterious Object - V838 Monocerotis

NIRIS and BASS Observations

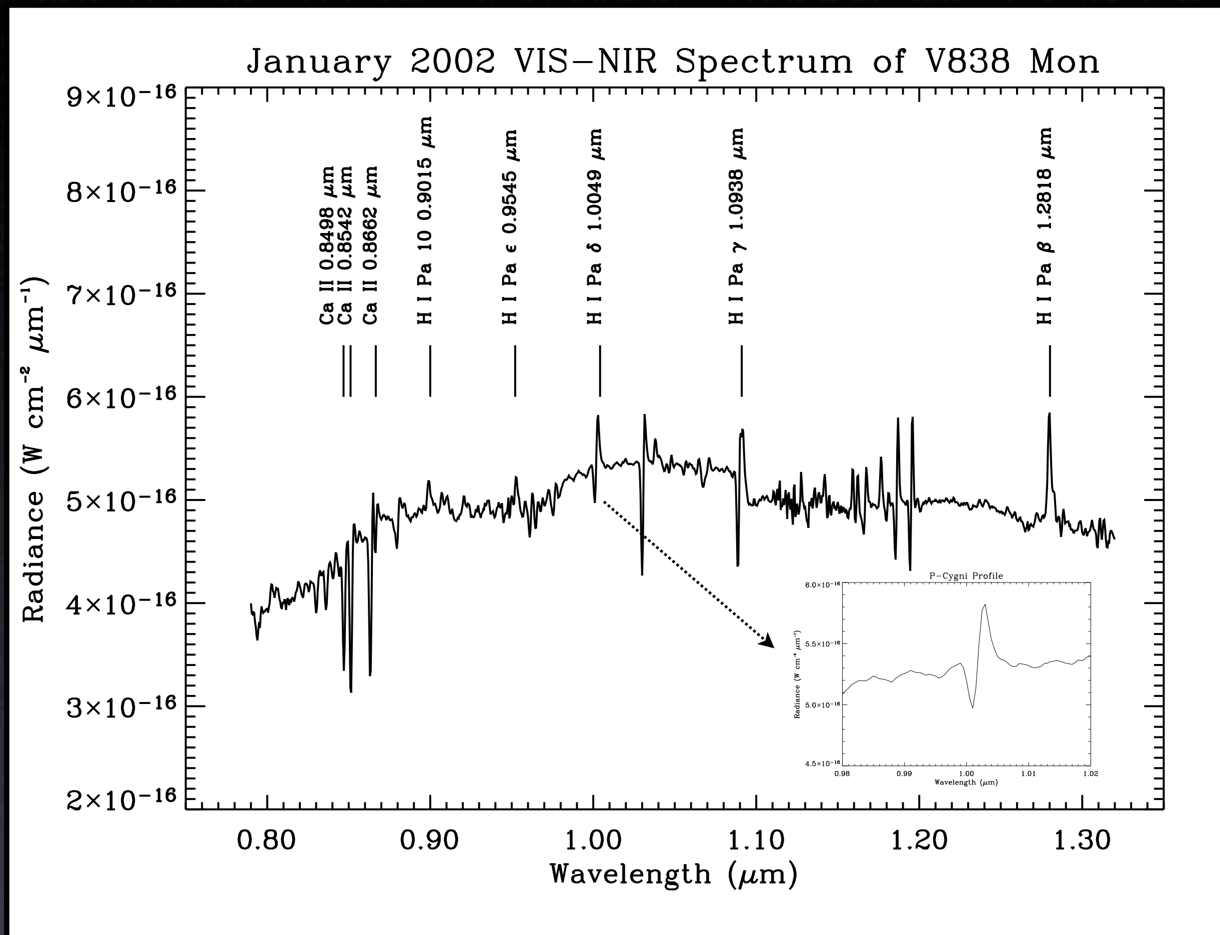


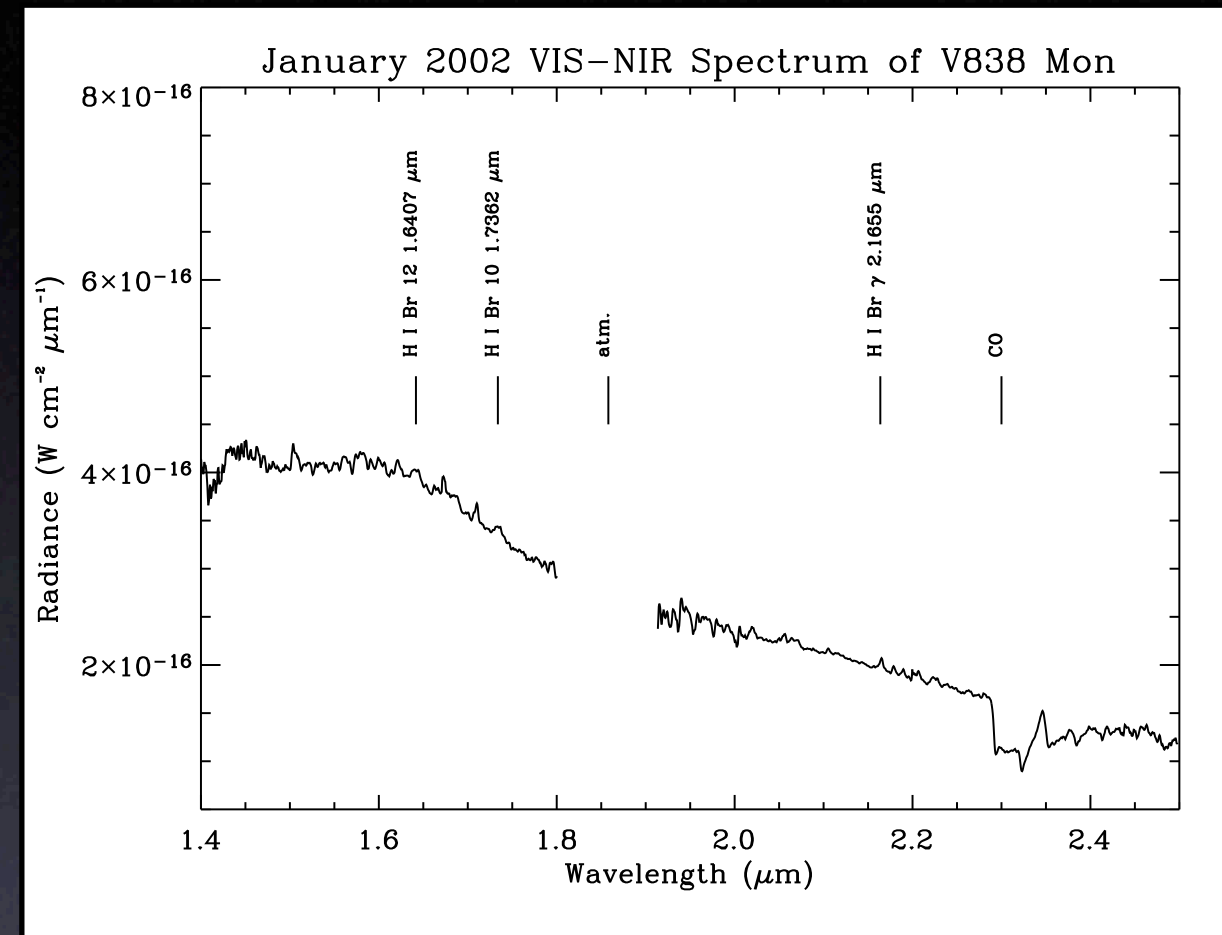


- Overall shape closely matched that of a 2700 K blackbody at all wavelengths which suggests the object was quasi-photospheric.
- By late 2002, the near-IR brightness had increased by a factor of 3 and the LWIR by a factor of 20. The J, H, K, L, M, N magnitudes went from 7.1, 6.3, 5.9, 5.2, 5.2, 4.5 in January 2002 to 6.8, 5.8, 4.7, 2.8, 2.5, 1.5 around December 2002.
- The large increase in the LWIR flux and the development of a strong infrared excess was most likely due to the formation of dust which has been confirmed from other measurements.

Mysterious Object - V838 Monocerotis

January 2002 NIRIS Observations

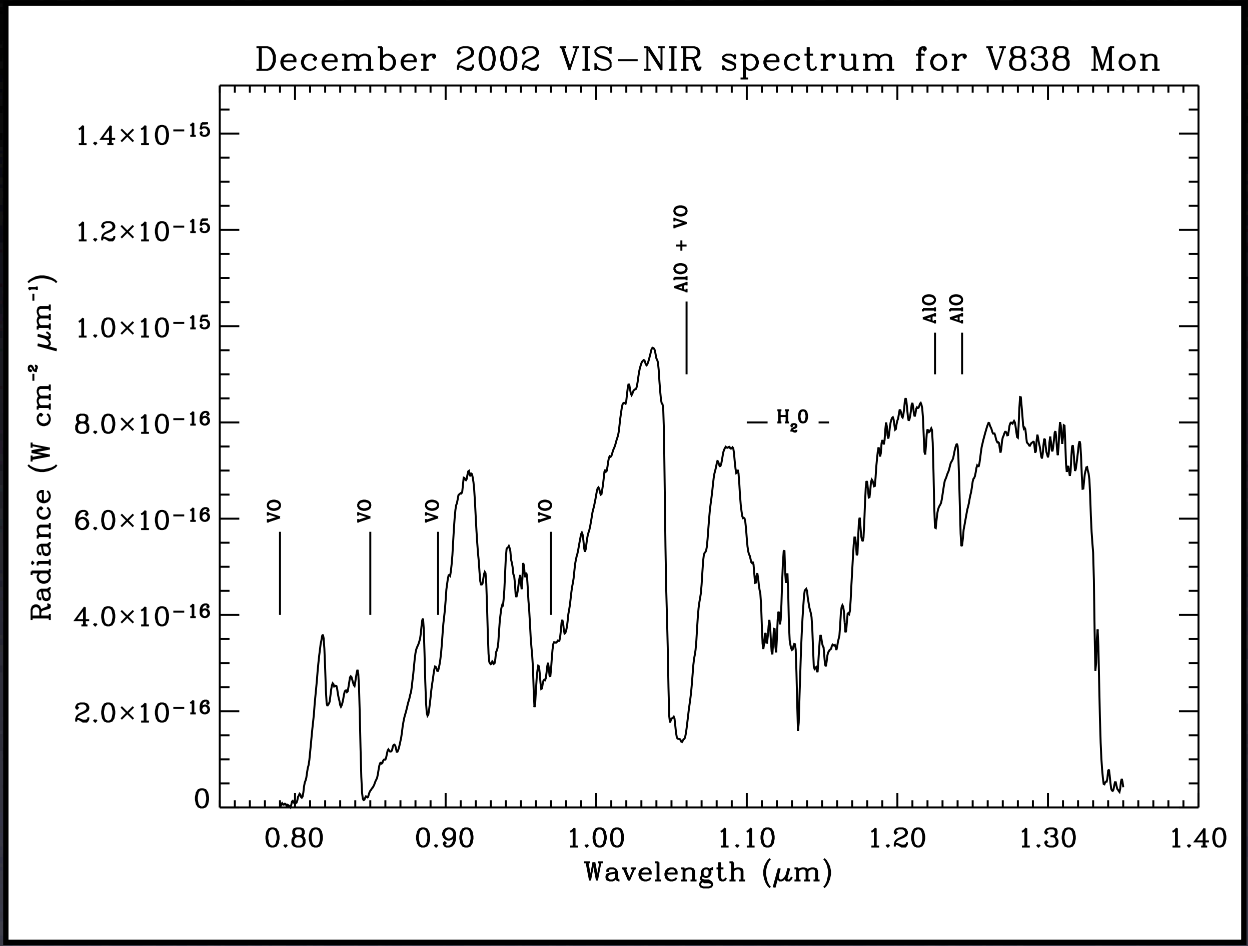


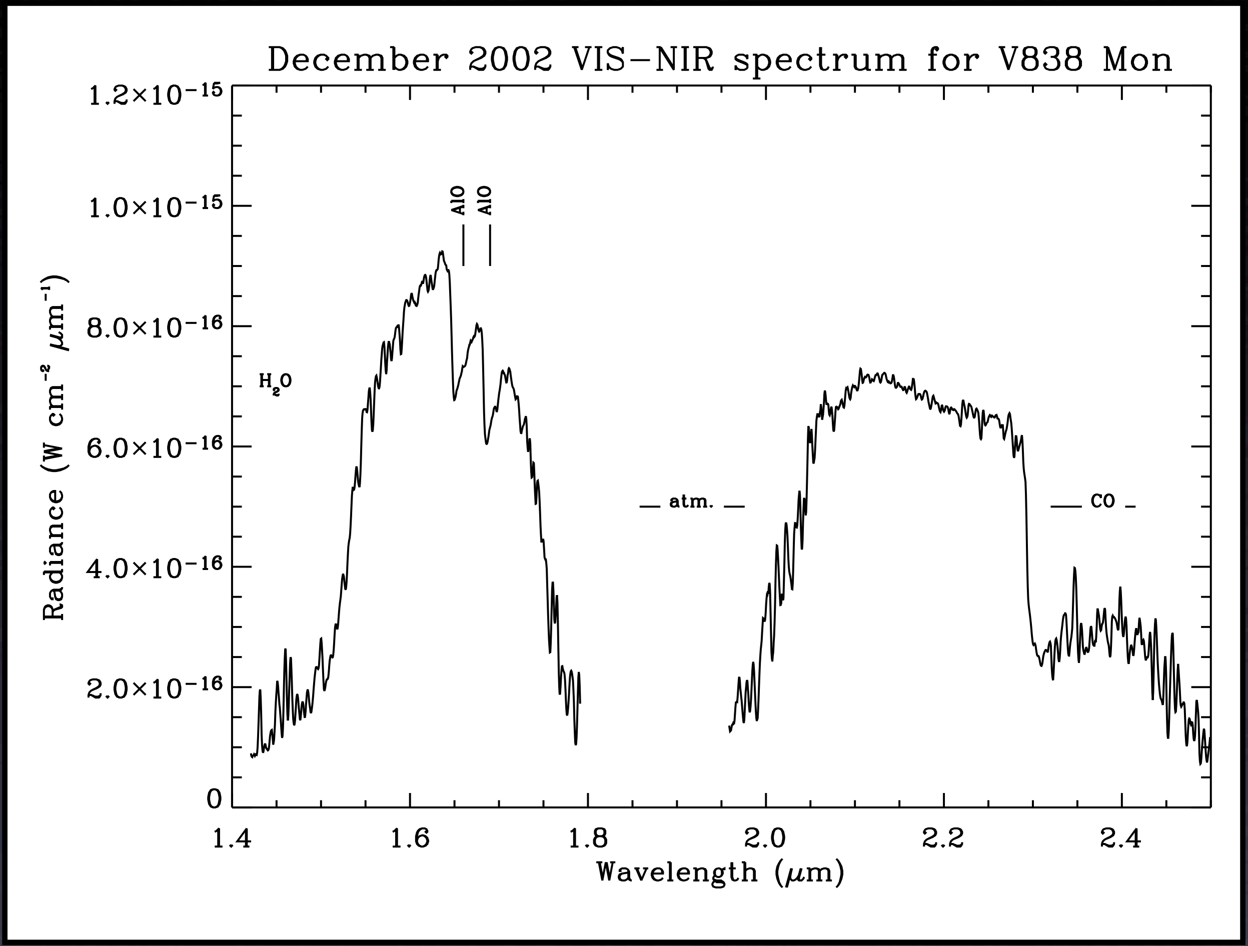


- This spectrum revealed a photospheric continuum.
- Strong emission lines with P-Cygni profiles and absorption features were present.
- The expansion velocity was about 500 km/s.
- Hydrogen Paschen and Bracket series lines dominate the spectrum and the Ca II triplet around 0.84 microns.
- A deep CO first-overtone band absorption near 2.3 microns was also present.
- Many other lines are present most likely from low abundant, high atomic number metals due to the *s*-process.

Mysterious Object - V838 Monocerotis

December 2002 NIRIS Observations

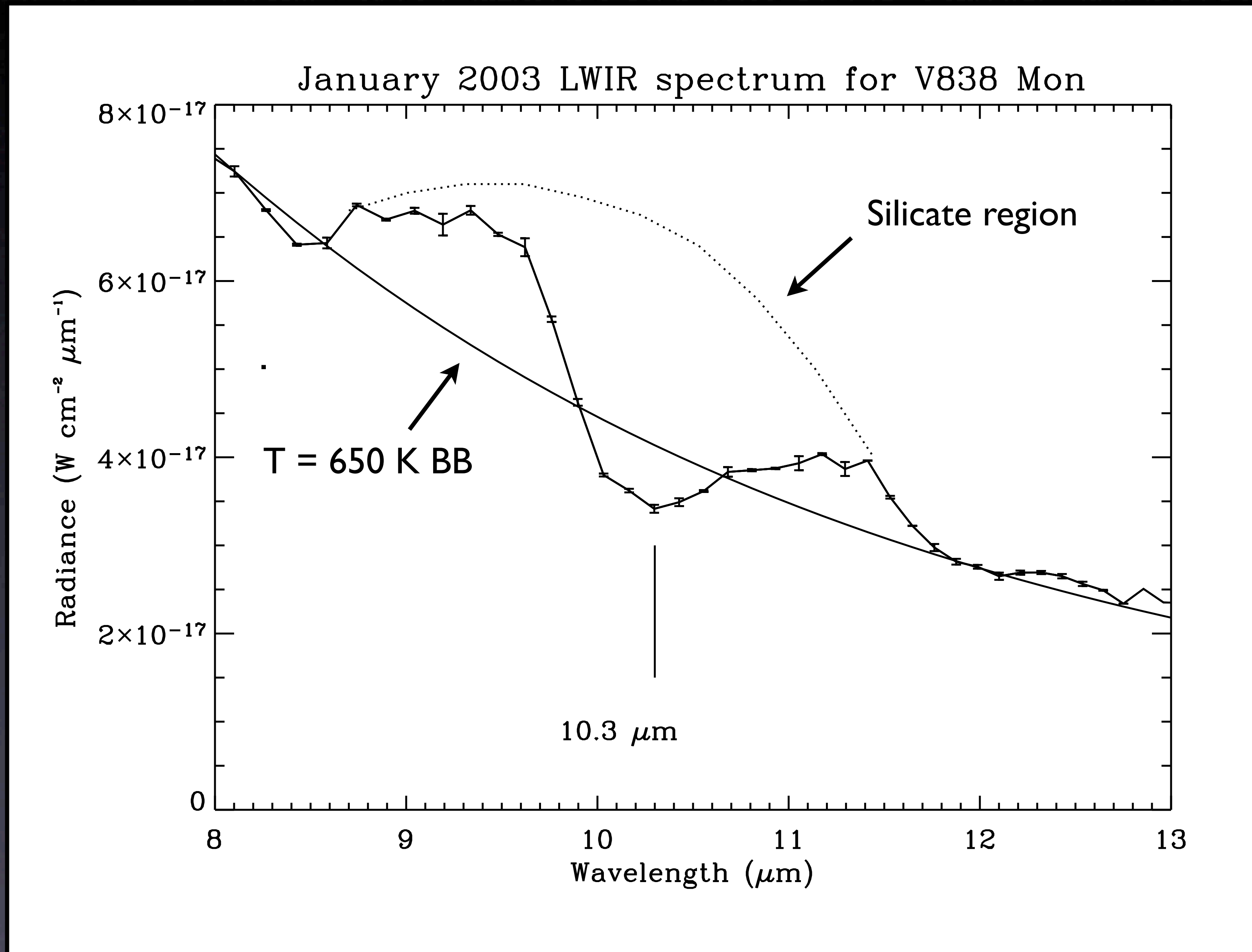




- In a year, the spectrum dramatically changed.
- The object cooled considerably and the spectrum was dominated by molecular bands of H2O, and CO.
- Significant absorption features due to aluminum oxide (AlO) and vanadium oxide (VO) were present (generally these features are seen in spectra of late type stars).
- Titanium oxide (TiO), which frequently dominates the spectra of late type stars, is less apparent in this spectrum.

Mysterious Object - V838 Monocerotis

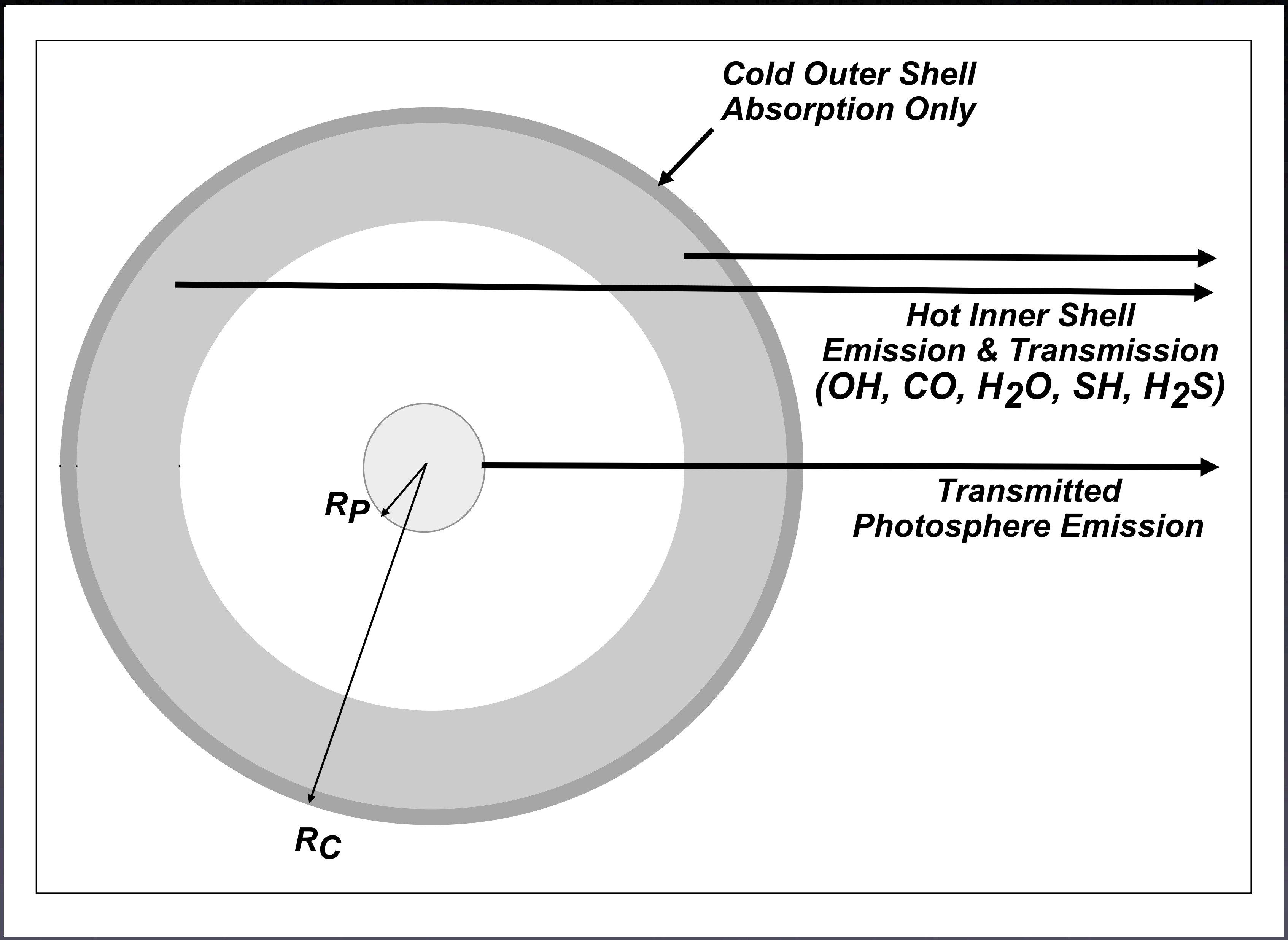
January 2003 BASS Observations



- The spectrum had a quasi-continuum and was fit to about a 650 K blackbody.
- A strong silicate emission feature with a well-defined central absorption was present.

Mysterious Object - V838 Monocerotis

Model Calculations

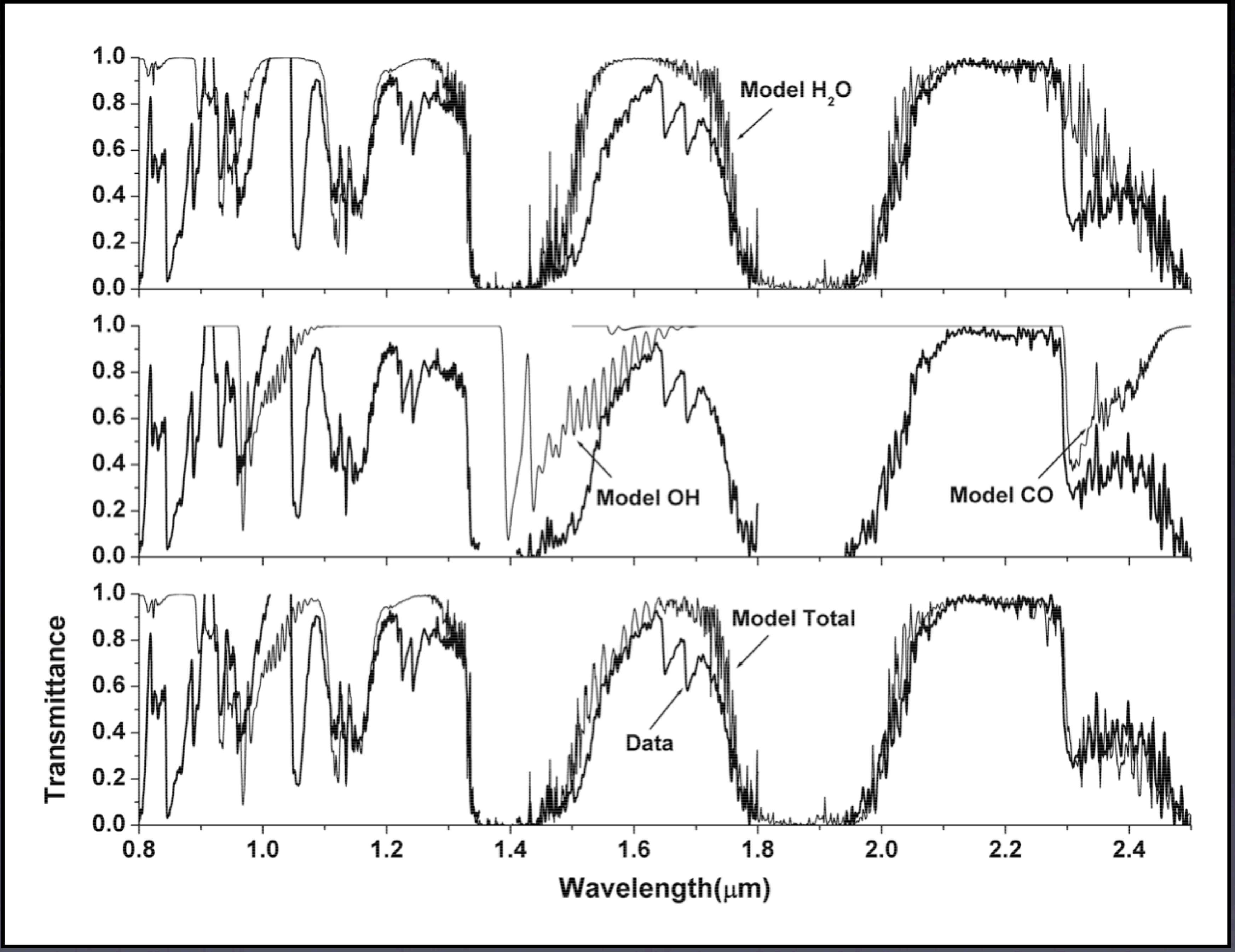


- Band model-based radiative-transfer approach accounting for optical opacity and velocity spreading in the expanding gas cloud.
- Two regions:
  - Photosphere
  - Expanding gas cloud (result of three separate outbursts)
    - cold absorption-only outer shell
    - hot emitting and absorbing inner shell

Mysterious Object - V838 Monocerotis

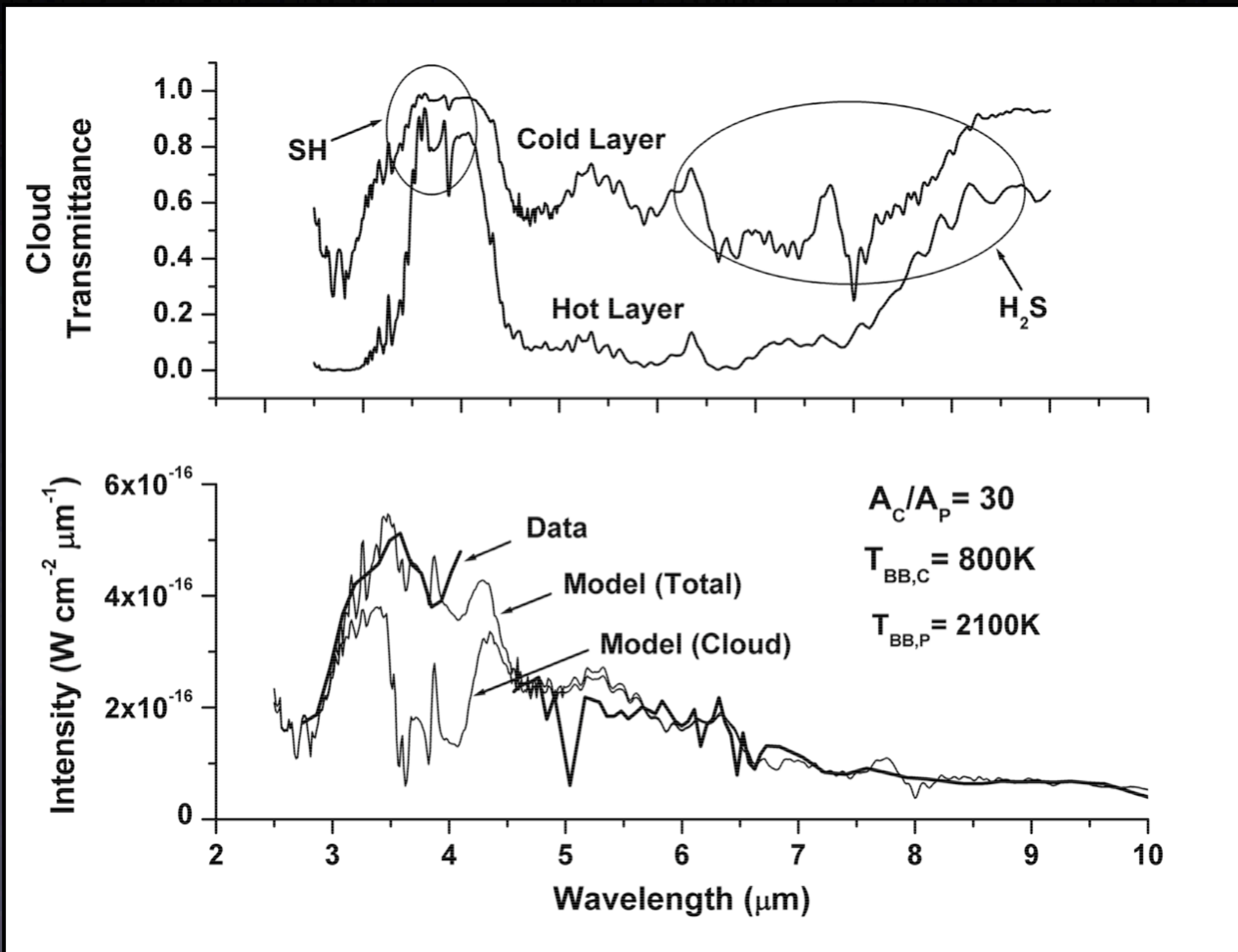
Model Calculations - Fit to Dec. 2002 VIS-NIR observations

- Highlights the role of molecular absorption in the expanding gas cloud
- Parameters:
  - T_{cloud} = 650 K
  - $T_{photosphere}$ = 2100 K
  - velocity spread of 52 km/sec (FWHM)
  - Column densities:
    - OH 1.0×10^{23} cm^{-2}
    - $H_2 0$ 1.6×10^{22} cm^{-2}
    - CO 8.0×10^{21} cm^{-2}



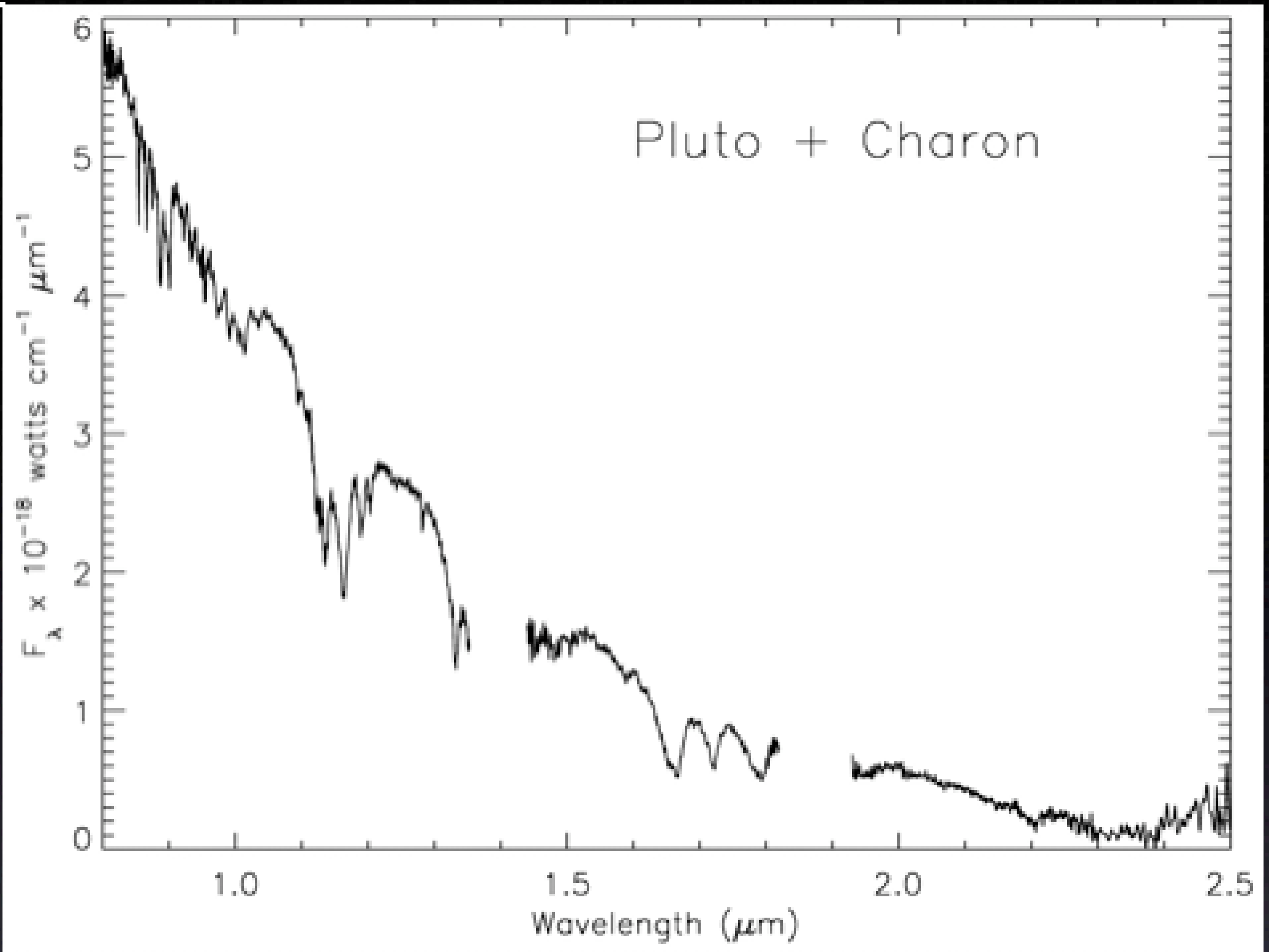
Mysterious Object - V838 Monocerotis

Model Calculations - Fit to Jan. 2003 Mid-IR & LWIR observations



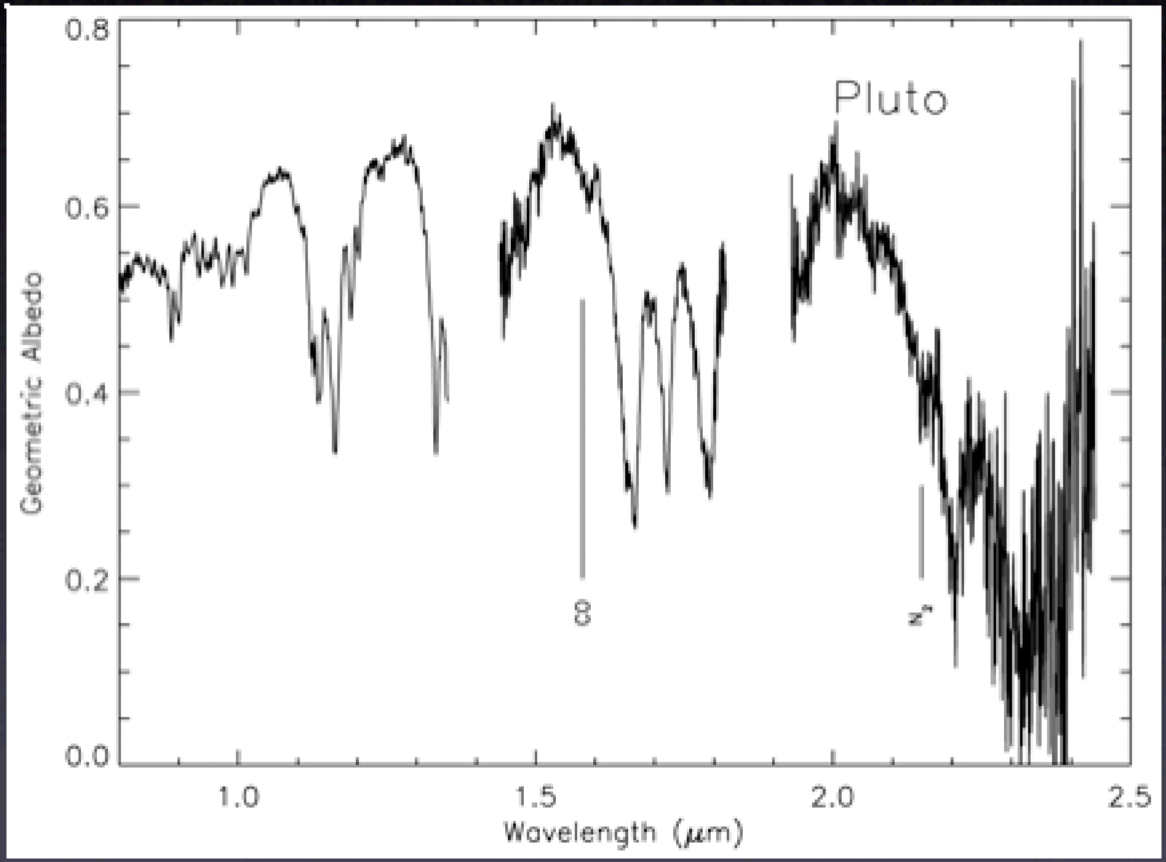
- Model considered emission from photosphere as well as the gas cloud
- Currently dust is not included in model - just molecules
- H_2S and SH present
  - from including the non-radiating cold outer layer to the gas cloud

Pluto



Near-infrared spectrophotometry of Pluto and Charon from 2002 July 18.25 UT. The deep broad absorption features are due to methane. The spectrum also shows solar absorption features. The strongest of these is the Ca II infrared triplet (at 0.8498, 0.8542, and 0.8662 microns) but Paδ and Paβ (at 1.0049 and 1.2818 microns) can be seen as well. The gaps in the data are due to regions of high telluric water vapor absorption.

Rudy, R.J., Venturini, C.C., Lynch, D.K., Mazuk, S., Puetter, R.C., Perry, R.B., PASP, 115, 484-489, 2003



Geometric albedo of Pluto at sub-Earth longitude of 80 degs. The small contribution from Charon has been removed. The weak absorptions of N_2 and CO are labeled; all other features are due to CH_4.

Modeling Novae

Restricted Three-Body Dynamics and Morphologies of Early Novae Shells and their Spectral Signatures

Modeling Novae

- Goals:
  - To understand the gravitational dynamics of mass ejection, especially early in the event
  - To predict line profiles for comparison to observations
  - To understand the late-time morphology and correlate with early-time phenomenology

Modeling Novae

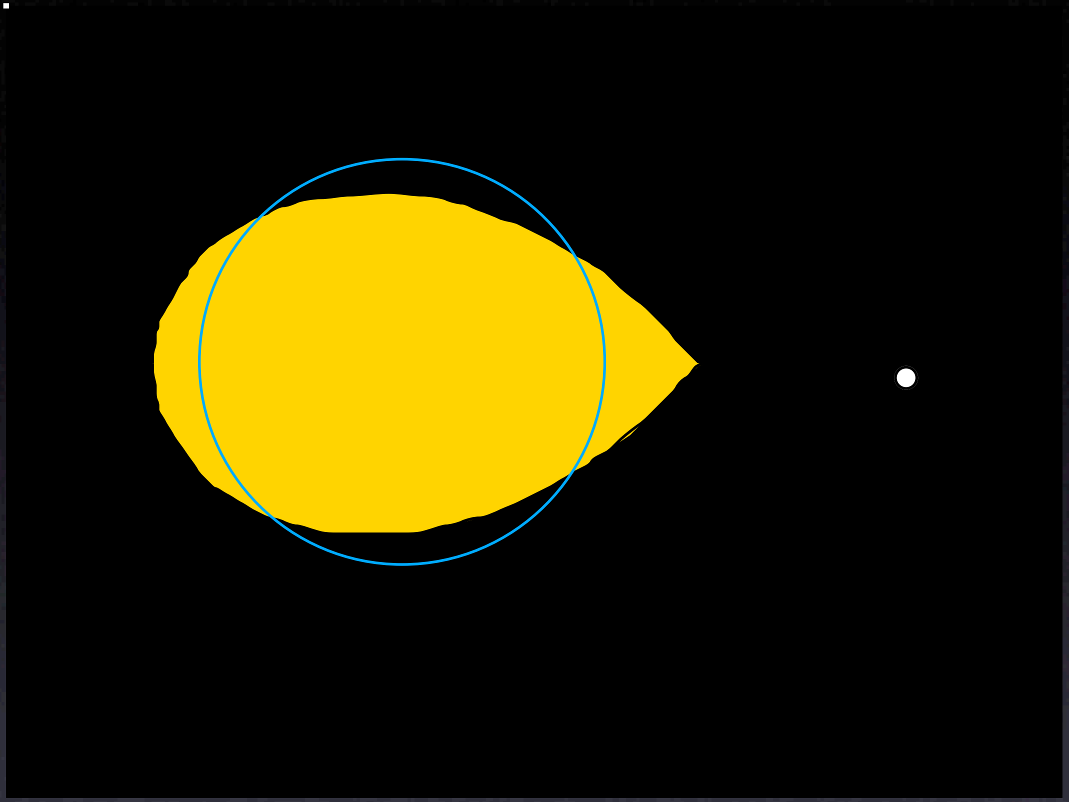
- Computations (10,000 points)
  - Numerically integrate the elliptic restricted three body equations in a non-dimensional form and in a rotating frame using a Runga-Kutta 7/8 integrator with adaptive time steps.
  - Particles ejected radially from the surface of the white dwarf with a radial velocity of magnitude Vo.
  - Particles are evenly spaced on the surface of the WD.
  - Assume only gravitational forces affect its motion.
  - If particle passes beneath the surface of either star, then integration stops and the particle is removed.
  - This is not a collisionless system.
  - Numerical accuracy: Jacobi Constant is continuously monitored changes greater than 1:10,000 are removed (<0.1%)

Modeling Novae

- Computation Caveats:
  - No radiation physics here. We're just moving particles around.
  - The "line profiles" are simple histograms of the projected particle velocities.
  - Shape and potential of the secondary are modeled as spherical.
  - Presently no interaction with the accretion disk or the ISM.
  - No viscosity, magnetic fields, etc.

Modeling Novae

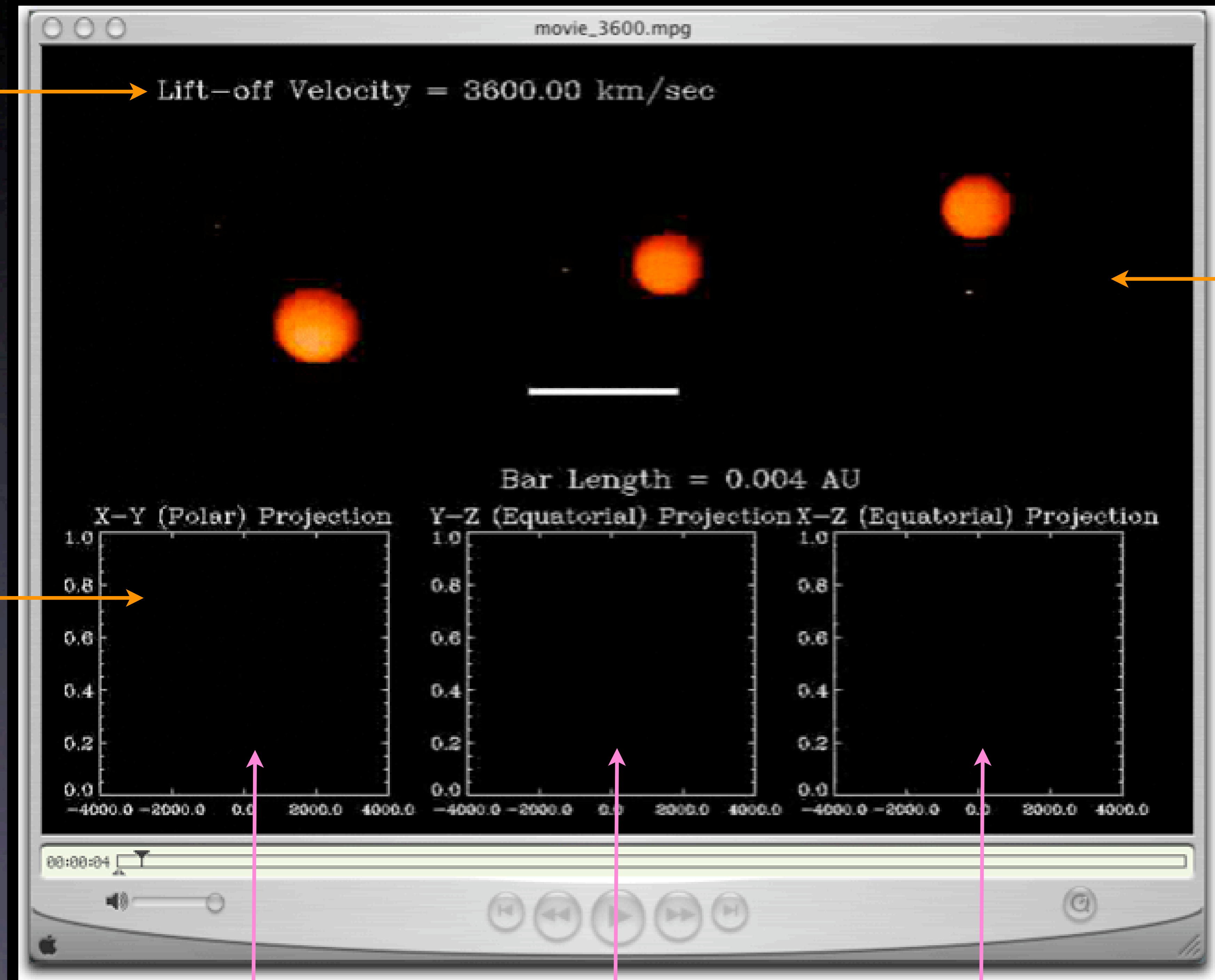
- Primary (WD)
  - Mp = 0.43 Mo
    Rp = 0.01 Ro
- Secondary
  - Ms = 0.21 Mo
    Rs ~ 0.4 Ro
- Orbit - circular
  - Semimajor axis = 0.00039 AU
    Period = 2 hrs 41 min
- Secondary potential modeled as a point source.
  Shape modeled as a sphere.
- Escape velocity - 3600 km/s



Modeling Novae

Movie

particle lift-off velocity from surface of WD (WD inertial centered frame)



Morphology

Line Profiles

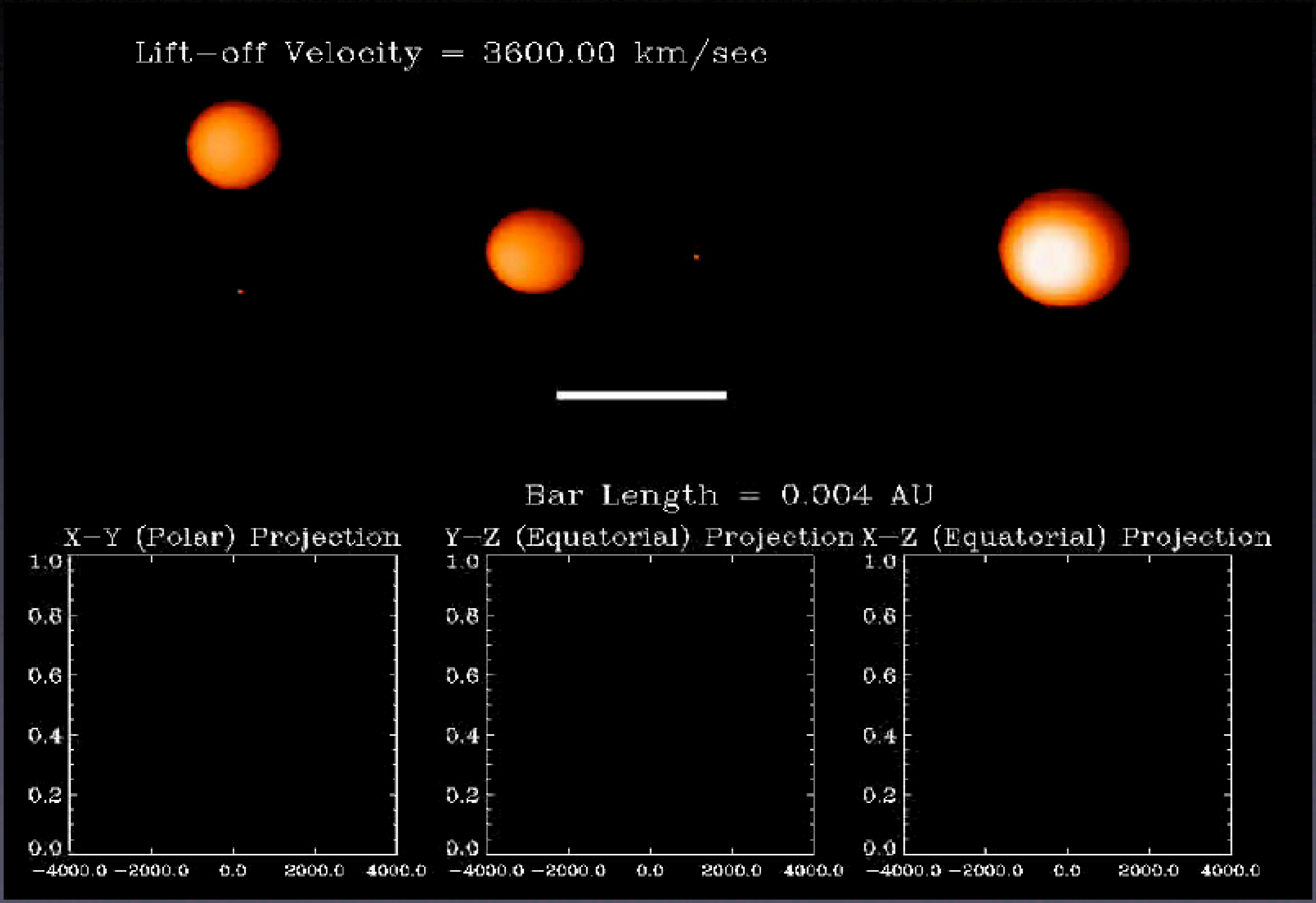
Polar

Equatorial 1

Equatorial 2

Modeling Novae

Movie



Concluding Remarks

- Novae are unique - no two are exactly alike
  - More observations are needed!
- IR spectroscopy offers a wealth of information
  - physical parameters as well as chemical evolution
- Exciting times for IR astronomy
  - SIRTF (launch August 2003) and SOFIA (2004)
    - provide order of magnitude improvements in astronomical capabilities

More Information...

Remote Sensing Department website:

http://www.aero.org/remote-sensing/